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Investigation of the Effect of Thermal Shields on the Calcination of Petroleum Coke in Rotary Disc Kilns

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Abstract:
Due to various impurities, impure petroleum coke obtained during extraction processes is unsuitable for optimal use. The calcination process, commonly called coke baking, has gained considerable attention for its ability to purify coke and remove waste materials. Various devices and methods are available for coke calcination, among which the rotary disc kiln has been investigated in this study. This research aims to propose a simple numerical model for simulating heat transfer processes within a rotary disc kiln. It was observed that during the layer-by-layer baking of coke, the intense heat flux of the gaseous phase inside the kiln leads to a rapid temperature rise in the first and second coke layers. To address this, a novel thermal shield was introduced in this study to reduce the heat flux reaching the coke bed in the initial layers. Results demonstrated that applying a thermal shield reduced the coke bed temperature in the first and second layers by up to 8% and 52%, respectively, while maintaining the overall calcination process. Increasing the shield's thickness by 20% decreased the temperatures by 7% and 17% in these layers. The model also achieved an accuracy of less than 2% error compared to reference data, confirming its reliability. Additionally, using the shield reduced the refractory lining temperature by up to 7.74%, improving kiln durability and energy efficiency.

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1. Introduction

Petroleum coke is extensively used as a fuel or carbon-rich additive in various industries, including cement manufacturing and the production of metallic anodes. Naturally occurring coke, often found in raw products, contains impurities and requires complex purification methods to achieve higher purity. Petroleum coke (pet coke) is a coal-like product produced while refining crude oil [1].

Raw petroleum coke, known as "green coke," contains over 90% carbon and, when burned, generates 5–10% more CO_2 per unit of energy compared to coal [2]. It has a higher calorific value than metallurgical coke and a lower ash content. Due to the extreme thermal conditions under which petroleum coke is produced, it has a very low content of volatile combustible materials. As a result, its low volatility makes it particularly difficult to burn.

High-purity petroleum coke is obtained through the calcination process. Calcination is an industrial process involving the thermal decomposition of mineral or organic materials without air or oxygen. During this process, the material is subjected to high temperatures, causing the decomposition of its compounds into simpler forms. Changes in material's chemical composition and molecular structure often accompany this transformation. Calcination is commonly applied in petroleum processing, aluminum production, steelmaking, and other chemical and mineral industries. The process involves heating materials to high temperatures in airless or low-oxygen environments, leading to decomposition and separation. This can result in the production of materials with unique properties and applications.

Figure 1 shows the various forms of calcined coke, including needle coke, sponge coke, and shot coke, highlighting their microstructural differences.

Table 1 illustrates the differences between green coke and calcined coke. As shown, a significant proportion of green coke comprises impurities and toxic substances. Removing these materials not only enhances the physical and thermal properties of the coke but also provides industries with cleaner fuel.

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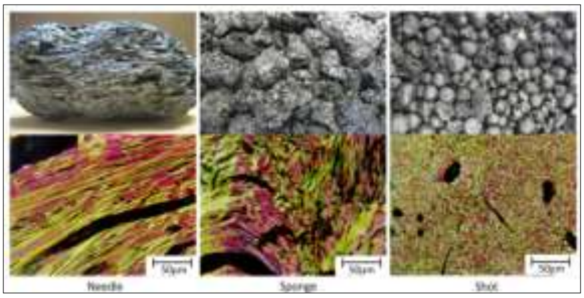

Figure 1. Different forms of calcined coke (Left: Needle coke, Centre: Sponge coke, Right: Shot coke) [2]

Table 1. Differences Between Uncalcined Coke and Green Coke [1]

Composition (Weight Percentage)	Green Coke	Calcined Coke
Fixed Carbon	80–90	98.5–99
Hydrogen	3–4.5	0.1
Nitrogen	0.1–0.5	-
Sulfur	0.2–6	-
Volatile Matter	5–15	0.2–0.9
Moisture	0.5–10	0.1
Ash Content	0.1–1	0.02–0.7
Bulk Density	1.6–1.2	1.2–1.9

The calcination process of green coke is carried out using various direct heating methods, commonly called coke baking. Coke baking can be performed in different designs and in different kilns. One of the most effective methods is using rotary disc kilns, a schematic of which is shown in Figure 2.

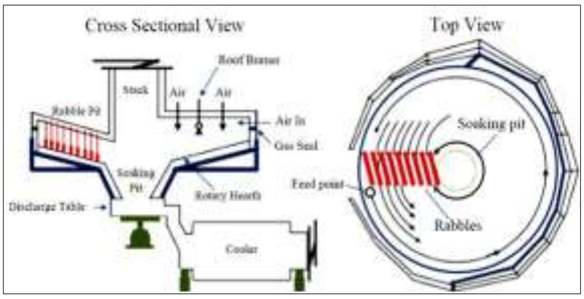

Figure 2. Cross-sectional views from the top and side of a rotary disc kiln [3]

Kocaefe et al. experimentally studied four types of green coke during the calcination process [3]. They compared the results by comparing the coke samples taken from the kiln in terms of density, particle size, porosity, and grain shape. They also investigated the effect of heating rates. The green coke samples were subjected to heating rates of 40, 90, and 150°C, and the final quality of the calcined coke was assessed. The study further explored the impact of retention time and heating duration in the kiln on the quality of the resulting coke. The findings indicated that extending the kiln retention time significantly enhanced the coke's final quality. Belitskus demonstrated that spherical coke particles calcined more effectively than plate-like or needle-shaped particles [4].

One of the first researchers to study heat transfer in rotary kilns was Pearce [5]. He investigated heat transfer between the gas phase and the coke bed (via radiation and convection) and within the coke bed (via conduction and radiation). This paper presented a heat transfer model for rotary kilns. The study's main objective was to develop an accurate model to simulate the heat transfer process in such kilns. The results showed that the model significantly improved the understanding and accuracy of heat transfer calculations in rotary kilns.

Cooling systems can enhance efficiency in energy-intensive processes. Arabi et al. [6] analyzed fog cooling for GE-F5 gas turbines in warm climates, showing improved turbine efficiency and reduced costs by lowering input air temperatures. This aligns with the current study's focus on using thermal shields to manage heat flux and stabilize temperatures, improving energy efficiency in industrial systems.

Bui et al. focused on the mathematical modelling of rotary disc kilns for calcining petroleum coke [7]. Using analytical methods and mathematical modelling, they examined and simulated rotary kilns' performance during pet coke's calcination. The study highlighted the critical factors influencing the calcination process and their effects on efficiency and productivity. The modelling results indicated that optimising kiln parameters could improve the overall performance of the calcination process. This research demonstrated that mathematical models could provide a more precise description of the calcination process. Key factors such as temperature, kiln rotation speed, and retention time were evaluated, and their optimisation was shown to enhance efficiency.

Nonlinear fractional differential equations (FDEs) have gained significant attention for their ability to model complex thermal and mechanical engineering systems. A recent study employing Akbari-Ganji's Method (AGM) demonstrated its efficiency in solving FDEs with high accuracy, providing a computationally efficient approach to analysing heat transfer mechanisms. Such advanced modelling techniques could complement the current study by offering additional tools to refine numerical simulations of thermal processes in rotary kilns, ensuring precision in temperature control and shield optimisation [8].

Martins et al. conducted a simulation study on the calcination process, focusing on the effects of various factors on process performance and efficiency [9]. Similarly, Elkanzi et al. simulated calcination processes in rotary kilns [10]. Their research involved using simulation techniques to analyse and predict the performance of coke calcination in such kilns. The primary goal was to study the impact of different parameters on the calcination process's quality and efficiency and to improve operating conditions. Simulation results showed that precise control of critical factors can significantly enhance the performance and quality of the calcination process.

Some studies have also focused on the kinetic analysis of the calcination process. Elkanzi et al. conducted a kinetic analysis of coke calcination in rotary kilns [11]. Using analytical methods, they investigated and predicted the kinetic behaviour of the calcination process in such kilns. The study's main objective was to determine the kinetic parameters and analyse the temporal behaviour of the calcination process.

Seasonal cold storage systems have been proposed as an innovative solution for improving energy efficiency in challenging climates. A study tailored for mountainous regions demonstrated the integration of ambient cold air and refrigeration technologies to reduce energy demand during peak summer months, achieving energy savings of 13.73% and peak load reductions of 8% [12]. The concept of conserving and redistributing thermal energy aligns with the principles of heat flux management employed in the current study, where a thermal shield is introduced to regulate temperature gradients in rotary kilns, reducing energy loss and improving operational efficiency.

A compact heat exchanger for industrial furnaces was optimised by Ghadamian et al. through mathematical modelling and computational tools. Significant energy savings were achieved, with the design's heat transfer efficiency validated experimentally, demonstrating its proximity to the theoretical optimum and economic feasibility [13]. Also, they developed a nonlinear model to optimise compact heat exchangers used as air pre-heaters in industrial furnaces. The design achieved minimal deviation from the optimal heat transfer rate, addressing key constraints such as tube configuration and dimensions to improve efficiency and practicality [14].

Thermal shields have been proposed as a novel approach to mitigate intense radiative heat fluxes in high-temperature processes. Studies such as those by Modest [15] discuss the principles of emissivity and reflectivity in controlling heat transfer. While these principles have been applied to furnaces, their integration into rotary kilns remains limited.

This study bridges these gaps by introducing a thermal shield to reduce heat flux in the initial layers of a rotary disc kiln. The study contributes to understanding heat transfer control in rotary kilns by examining the effects of shield placement and thickness.

In addition, controlling the calcination process in rotary kilns improves coke properties. One of the challenges in coke calcination is the rapid temperature rise at the kiln's inlet. Green coke, typically introduced at ambient temperature without preheating, is subjected to high heat flux from the hot gases in the initial layers of the rotary disc. This can result in the fragmentation and pulverization of the coke. Therefore, implementing measures to reduce this intense heat flux is crucial. In this study, a thermal shield was utilized to mitigate the excessive heat flux in the first two layers of the coke bed.

2. Research Methodology

The thermal analysis of rotary disc kilns requires a comprehensive understanding of the behaviour and properties of all components involved. Figure 3 shows the calcination process of coke in a rotary kiln.

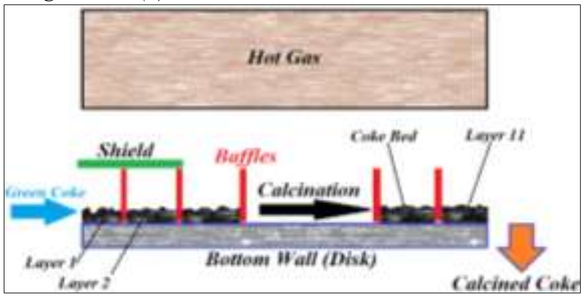

Figure 3. The calcination process of coke in a rotary disc kiln

Green coke is initially introduced into the kiln and rotates along the outermost diameter of the disc for one complete cycle. It is then transferred through a baffle between the first and second layers into a new pathway closer to the center of the disc, where the calcined coke is eventually discharged. Each baffle moves the coke mass from one layer to the next until, after approximately 11 rotations (depending on the disc dimensions and its rotational speed), the coke is fully calcined.

Each circular pathway of coke rotation is referred to as a "layer" or "passage." The rotation radius varies for each layer, and the coke mass in each layer completes an entire cycle before being transferred by the baffles to a layer closer to the center for eventual discharge. The coke part directly exposed to the hot gas is known as the coke bed or surface. While the coke bed is not perfectly flat and has some irregularities, these irregularities are negligible compared to the thickness of the coke layer. Therefore, in this study, the bed is assumed to be completely flat, and the coke thickness is considered uniform across all sections.

As shown in Figure 3, the thermal shield, with a specified thickness, is placed over the first or second layer of the coke bed during calcination. Its purpose is to prevent rapid heat transfer to the coke, thereby reducing the risk of cracking and pulverization. It is anticipated that using the thermal shield will improve the quality of the calcined coke.

2.1. Heat Transfer in the Kiln

In industrial kiln studies, heat transfer is considered one of the critical aspects of operation. Heat transfer in rotary disc kilns occurs through radiation, conduction, and convection. These heat transfer forms occur between the coke bed, the gas phase, and the refractory lining, as illustrated in Figure 4 [16].

As shown, all three modes—radiation, conduction, and convection—contribute to the heat transfer process, and the combination of these mechanisms influences the final temperature of each kiln component. Table 2 provides descriptions of each heat transfer component within the kiln.

This study calculates the heat transfer rates, as well as the coke bed temperature, the average coke temperature, and the refractory lining temperature. The relative importance of the heat transfer modes depends heavily on temperature. In some cases, all three types of heat transfer are present. For example, heat transfer from the refractory lining on the roof occurs primarily through radiation (due to the very high temperature). Still, the other two modes of heat transfer also exist to a lesser extent. Therefore, in high-temperature processes, radiative heat transfer becomes the dominant mode.

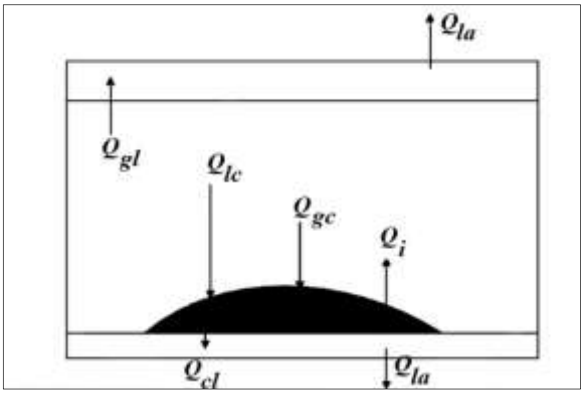

Figure 4. Heat transfer between the coke bed (c), gas phase (g), ambient air (a), and refractory lining (l) [16].

Table 2. Descriptions of All Heat Transfer Modes Within the Kiln

Parameter	Description
Q_{gc}	Convective heat transfer between the gas and the coke bed.
Q_{cl}	Conductive heat transfer between the coke bed and the refractory lining at the bottom.
Q_{lc}	Radiative heat transfer between the refractory lining on the roof and the coke bed.
Q_{la}	Convective heat transfer between the refractory lining on the bottom and ambient air.
Q_{gl}	Convective heat transfer between the gas and the refractory lining on the roof.
Q_i	Heat transfer from the coke to the gas.

2.2. Radiative Heat Transfer

The following assumptions are made when determining the radiative heat transfer between the kiln components:

1. All radiative properties are considered for all components.
2. The coke bed and the walls are assumed to be opaque.

$$\varepsilon = \alpha \quad (1)$$
$$\tau = 0 \rightarrow \rho = 1 - \alpha \quad (2)$$

The gas inside the kiln is assumed to be opaque and non-reflective to heat. The governing equations for radiative heat transfer, including emissivity, absorptivity, reflectivity, and transmissivity, are derived from standard formulations found in thermal engineering texts [17]. These parameters are defined in Table 3.

$$\varepsilon_a = \alpha_a \quad (3)$$

Thus, all radiative heat transfers within the kiln can be summarized as follows.

$$\Phi_{r,gc} = F_{gc}.\frac{\varepsilon_g+1}{2}.\sigma.\varepsilon_g.\left(T_g^4 - T_c^4\right) \quad (4)$$
$$\Phi_{r,gl} = F_{gl}.\frac{\varepsilon_l+1}{2}.\sigma.\varepsilon_g.\left(T_g^4 - T_l^4\right) \quad (5)$$
$$\Phi_{r,cl} = F_{cl}.\varepsilon_l.\varepsilon_c.\left(1 - \varepsilon_g\right).\sigma.\left(T_c^4 - T_l^4\right) \quad (6)$$

Equations 4 to 6 represent the radiative heat transfer between the coke and the gas, the gas and the walls, and the coke and the walls, respectively. In these equations, F denotes the form factor between each pair of heat transfer components, T represents the temperature of each component, and σ is the Stefan-Boltzmann constant.

Table 3. Parameters for Equations (1) to (3)

Parameter	Description
ε	Emissivity
α	Absorptivity
ρ	Reflectivity
τ	Transmissivity

2.3. Conductive Heat Transfer

The governing equation for conductive heat transfer is based on Fourier's law, which states that the heat flux is proportional to the temperature gradient [18].

$$\Phi_{cond} = -k\nabla T \quad (7)$$

In this context, k represents the conductive heat transfer coefficient, and T denotes the temperature. Conductive heat transfer is disregarded in the gas phase but must be accounted for in the coke bed and kiln walls. However, in these components, conductive heat transfer is assumed to occur in one dimension.

Determining the conductive heat transfer coefficient is this section's most critical parameter for calculations. This study considers the coke bed a thick medium for conductive heat transfer. According to Kreith and Black, whether a medium is classified as thick or thin in conductive heat transfer is determined by a parameter known as the Biot number [19].

$$Bi = \frac{hV}{kA} \quad (8)$$

The effective parameters are presented in Table 4.

Table 4. Parameters for Equation 8

Parameter	Description	Unit
h	Heat transfer coefficient from the gas or walls to the coke bed	[J/m²K]
V	Volume of the medium under heat transfer	[m³]
k	Thermal conductivity coefficient	[W/mK]
A	Heat transfer surface area	[m²]

Thus, if the volume of the medium under heat transfer is large, the Biot number will also be significant, and the heat transfer process can be considered as occurring in a thick medium. Generally, for Biot numbers greater than 1, the medium can be assumed to be thick for heat transfer. Accordingly, the effect of thickness must be properly accounted for.

Figure 5 shows the thermal conductivity coefficient of the coke bed (in W/m K) as a function of temperature [20]. Heat losses due to radiation and convection from the outer wall of the kiln are discussed in the following sections.

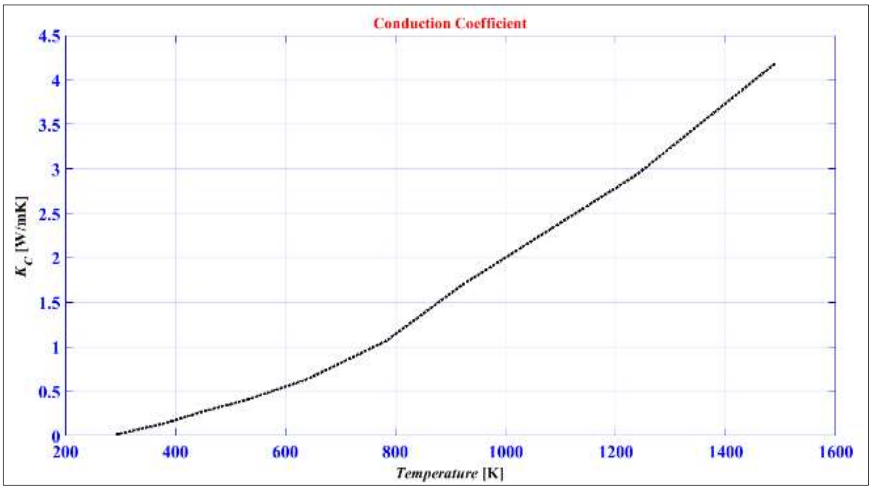

Figure 5. **Effective thermal conductivity of the coke bed as a function of temperature [16]**

In luminous flames, ε_g can be assumed to be equal to 1 [9]. For the gas temperature (T_g), a value of 1000°C can be considered. Additionally, $c_{\varepsilon c}$ is equal to 0.8, k is equal to 1, and the height of the coke bed is 0.2 [16]. The values of h_{eff} and B_i for two different coke temperatures are shown in Table 5 [16].

Table 5. **Values of Parameters h_{eff} and B_i for Sample Coke Temperatures [16]**

Coke Temperature (°C)	h_{eff}	B_i
100	73	15
500	115	23

Thus, given the very high Biot number values, the coke bed can be considered a thick medium, and the heat transfer can be assumed to occur in one dimension. Heat transfer to the coke bed results from all three types of heat transfer, and it is not feasible to clearly distinguish the effect of each type of heat transfer from the others. Therefore, a parameter must be determined for each heat transfer type to represent each transfer mode's effective coefficient. According to the study by Kolbeinsen, the following equation can be used to determine the effective heat transfer coefficient for conduction [21].

$$k_{eff} = \left(1 - \sqrt{1-\varepsilon_b}\right)k_R \frac{\sqrt{1-\varepsilon_b}}{\frac{1}{k_R}+\frac{1}{k_p}} \quad (9)$$

The parameter b_ε represents the percentage of void spaces in the coke bed, and k_R is derived from radiation, which can be calculated using the following equation.

$$k_R = \frac{0.04C_R}{\frac{2}{\varepsilon}-1} . \left(\frac{T}{100}\right)^3 . d_p \quad (10)$$

The term k_p refers to the conductive heat transfer coefficient from one particle to the surrounding particles, considering the porosity.

$$k_p = k_s\left(1-\varepsilon_p\right) \quad (11)$$

In these equations, the parameters are defined as shown in Table 6.

Table 6. **The parameters of Equations 9 to 11**

Parameter	Unit	Description
d_p	[m]	Average diameter of coke particles
ϵ	[-]	Porosity of particles
T	[K]	Average temperature of the coke bed
C_R	[-]	Constant
k_s	[W/mK]	Thermal conductivity for a heterogeneous particle

2.4. Convective Heat Transfer

The governing equations for convective heat transfer, represented in Equations 12 to 14, are formulated based on Nusselt number corrections and standard heat transfer correlations for forced convection [22].

$$\Phi_{c,gc} = h_{gc}.\left(T_g - T_c\right) \quad (12)$$

$$\Phi_{c,gl} = h_{gl}.\left(T_g - T_l\right) \quad (13)$$

$$\Phi_{c,la} = h_{la}.\left(T_l - T_a\right) \quad (14)$$

The parameters are presented in Table 7.

The convective heat transfer coefficient is obtained by correcting the Nusselt number (Nu) [17].

$$Nu = \frac{hd}{k_g} \quad (15)$$

where h is the convective heat transfer coefficient, d is the hydraulic diameter, and kg is the thermal conductivity of the gas. The convective heat transfer between the gas and the lining and between the gas and the coke bed is known as forced convection.

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Table 7. The parameters of Equations 12 to 14

Parameter	Unit	Description
h_{gc}	[J/m²K]	Convective heat transfer coefficient from gas to coke surface
h_{gl}	[J/m²K]	Convective heat transfer coefficient from gas to wall
h_{la}	[J/m²K]	Convective heat transfer coefficient from wall to ambient air
T_c	[K]	Temperature of coke
T_g	[K]	Temperature of gas
T_l	[K]	Temperature of wall
T_a	[K]	Temperature of ambient air

2.5. Thermal Shield Effect

The temperature of the coke entering the furnace is assumed to be 25°C. In this study, the coke enters the furnace without preheating. Consequently, due to the rapid temperature increase in the initial layers of the coke, the coke can crack and eventually disintegrate into powder. Additionally, the coke may become excessively porous by the end of the process. Therefore, controlling the heat flux applied to the coke in the initial layers is one of the key measures to consider.

In this study, a 1-mm-thick aluminum sheet is used on the first and second layers of coke in the furnace, as shown in Figure 3**.** This shield reduces the heat transferred to the coke bed by reflecting thermal radiation emitted from the gas toward the coke bed. As a result, the coke temperature in the first two layers does not increase rapidly.

The reflectivity of pure aluminum varies across different wavelengths, but it is consistently above 0.85. The wavelength of the radiation emitted by the hot gas at temperatures above 2000°C ranges from 0.1 to 100 micrometres. Therefore, as a reasonable assumption, the reflectivity of the aluminum sheet used in this study is 0.9. Figure 6 illustrates the variation in aluminum reflectivity across different wavelengths.

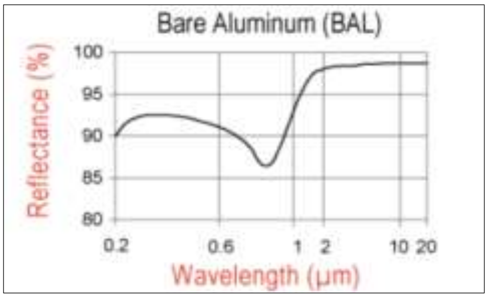

Figure 6. The reflectivity of pure aluminum at different wavelengths [3]

The shield's reflection of thermal radiation is governed by reflectivity and emissivity principles, as outlined in radiative heat transfer literature [15]. This reduction in heat flux lowers the temperature in the first and second coke layers. However, the portion of the radiation that is not reflected passes through the thickness of the aluminum sheet as conductive heat transfer. It is then re-emitted as radiation to the coke bed. Consequently, increasing the thickness of the aluminum sheet further reduces the conductive heat transfer. Table 8 provides the composition and impurity levels of the green coke used in the furnace, highlighting its weight percentages of key impurities such as moisture, volatile matter, and sulphur.

Table 8. Characteristics of the green coke entering the furnace

Impurity Type	Weight Percentage (%)
Moisture	1.8
Volatile matter	10.1
Ash	0.3
Zinc	0.002
Nickel	0.015
Iron	0.018
Vanadium	0.002
Calcium	0.007
Sulphur	3.2
Silicon	0.031
Titanium	0.004
Sodium	0.002

In an innovative approach, this study initially used an aluminum sheet with a thickness of 1 mm and then a sheet with a thickness of 1.2 mm (20% thicker) was tested to observe its effect on the coke bed temperature in the first two layers.

The quality of coke includes density, crystal size, and porosity. Low porosity, high density, and larger crystal sizes (avoiding fine or powdered coke) are the desired characteristics of the output coke and are among the objectives of this study. Kokaev et al. [3] proposed a model to determine the quality of coke. This model was developed by fitting curves to experimental data based on coke retention time, outlet temperature, and heating rate. The equation is expressed as follows [3]:

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \quad (16)$$

The coefficients of this fitted equation are provided in Table 9.

Table 9. The coefficients of Kokaev's model for coke quality [3].

Vertical Axis	Horizontal Axis	a_3	a_2	a_1	a_0
Density	Outlet Temperature	-4.003×10^{-9}	1.037×10^{-5}	-7.548×10^{-3}	3.024
Porosity	Outlet Temperature	2.755×10^{-8}	7.104×10^{-5}	-5.333×10^{-2}	18.12
Density	Retention Time	5.144×10^{-7}	-7.87×10^{-5}	4.06×10^{-3}	1.995
Porosity	Retention Time	-1.506×10^{-5}	4.111×10^{-4}	3.589×10^{-2}	8.84
Crystal Size	Retention Time	0	-2.177×10^{-3}	2.601×10^{-1}	22.02

The model presented in the previous section was coded using MATLAB software. The results obtained include thermal outputs, coke quality and properties and the effects of the thermal shield under different scenarios. In this study, the coke's density, porosity, and crystal size are presented as a function of the coke's outlet temperature from the furnace and its retention time. Thermal analyses were conducted for three key components of the furnace. The temperatures obtained during the calcination process include the temperature of the coke bed, the average temperature along the coke thickness, and the lining temperature.

The effect of the thermal shield was examined under four scenarios:

1. No thermal shield was used.
2. A thermal shield with a thickness of 1 mm was placed on the first layer.
3. The same thermal shield was placed on the first two layers.
4. The fourth scenario differs from the third only in the thickness of the thermal shield.

2.6. Grid Independence

This study considered the number of grid points as 50, 80, 110, 150, and 200. The coke temperature at the furnace outlet was measured, and the results were compared. Grid independence is achieved when the temperature difference between two consecutive grids is less than 1%. Table 10 presents these values for the last layer (layer number 11) at the time of coke exit

Table 10. Coke bed temperature at the furnace outlet (layer 11) for different numbers of grid points

Grid Points	Temperature (K)
50	1334.86
80	1379.26
110	1440.36
200	1441.45
300	1441.7
400	1441.75

As shown in Table 10**,** the coke bed temperature does not differ significantly between 110 and 200 grid elements, and the values have stabilized. Therefore, 110 computational points are used for ease of calculation. Additionally, the grid independence plot is presented in Figure 7.

2.7. Assumptions in Numerical Modeling

In this study, the following key assumptions were made for the numerical modeling of heat transfer in the rotary disc kiln.

2.8. Material Properties

- The coke bed is assumed to have a uniform density and porosity. The thermal conductivity of the coke bed is considered temperature-dependent and is modelled using empirical data (Figure 5).
- The refractory lining is treated as a homogeneous material with a fixed thermal conductivity of 2.5 W/m K.
- The gas inside the kiln is assumed to be a non-reflective and opaque medium with a uniform thermal conductivity of 0.05 W/m K.
- The emissivity of the coke bed, refractory lining, and gas were assigned values of 0.8, 0.9, and 1.0, respectively.

2.9. Computational Parameters:

- A grid independence study was conducted, with 110 grid points chosen for balancing computational efficiency and accuracy.
- The temporal resolution of simulations was set to ensure a Courant–Friedrichs–Lewy (CFL) condition below 0.5 for numerical stability.
- The convergence criterion for residuals was set at 10−6 for all energy equations.

2.10. Boundary Conditions:

- The kiln walls are considered adiabatic except for heat loss to the environment, modelled as convective heat transfer with a coefficient of 25 W/m² K.
- The initial temperature of the green coke is assumed to be 25°C, entering without preheating.

3. Results and Discussions

To validate the model presented in this study, the obtained results were compared with the reference numerical results [16]. Finally, the error between the two was evaluated. As shown in Table 11**,** the coke bed temperature was calculated from the end of the first layer to the end of the eleventh layer. The obtained values were compared with the reference data, revealing an error of less than 2%.

The coke bed temperature was considered as a function of its axial coordinates, from the outermost path (green coke entry) to the innermost path (near discharge).

Table 12 presents the lining temperature in different layers. Like the coke bed, the lining temperature increases very rapidly. The main reason for the increase is radiative heat transfer. Like the coke bed, the lining temperature stabilizes after the rapid growth.

In the calcination zone, the bed temperature for some furnaces can reach approximately 1400°C or higher, and the coke may remain at this temperature for nearly half the length of the furnace. Such prolonged heating times are sufficient to influence grain size and crystallinity, which contribute to improved product quality. Table 13 summarizes the heat flux values for different components of the furnace during a full rotation of the disc, including heat transfer between the lining, environment, gas, and coke surface, which are critical for understanding the energy dynamics in the calcination zone.

In some operations, calcined coke is cooled by directly spraying water onto the bed material in the cooler. This is done to dissipate the excessive combustion heat released by the oxidation reactions of carbon particles in the coke. Water has a positive annealing effect on grain structure. However, there is no evidence or study regarding the impact of steam pressure on crystal size in direct-fired furnaces, even though most combustion products from volatile matter would be water.

Figure 8 illustrates the coke bed temperature, the average coke temperature, and the lining temperature as a function of the total retention time of the coke in the furnace. As observed, the temperature of each component stabilizes after a certain period. The coke bed temperature at the furnace outlet is approximately 1500°C, while the lining and average coke temperatures are approximately 1200°C and 1100°C, respectively.

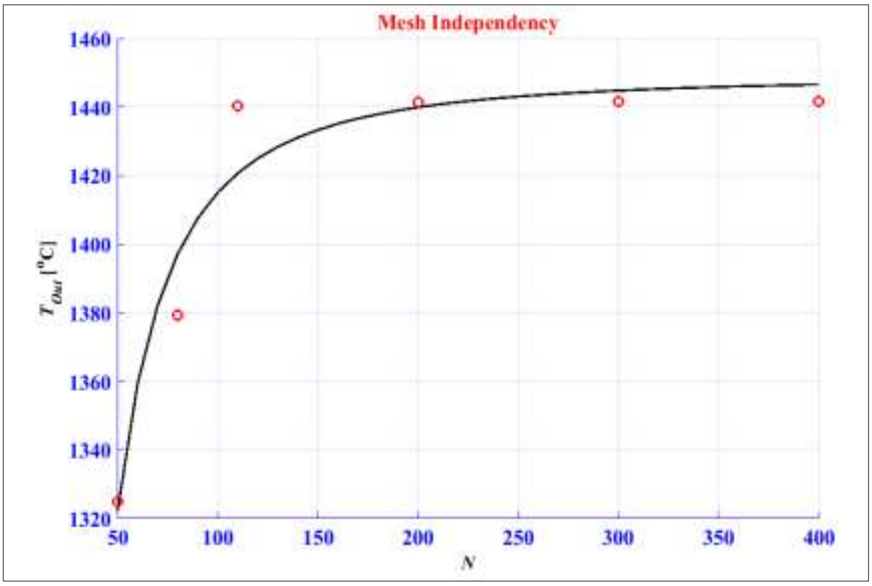

Figure 7. **Grid independence plot**

Table 11. **Coke bed temperature at the end of various layers and comparison with the reference [16]**

Layer Number	Simulated Temperature (°C)	Numerical Results [12] (°C)	Error (%)
1	156.01	157.26	0.24
2	381.01	381.52	0.12
3	600.98	602.77	0.29
4	804.25	802.64	0.20
5	1007.18	1007.78	0.01
6	1289.61	1287.61	0.16
7	1396.14	1391.98	0.12
8	1400.56	1398.25	0.15
9	1410.09	1405.71	0.04
10	1440.12	1439.22	0.07
11	1440.36	1440.05	0.06

Table 12. **Lining temperature at the end of various layers and comparison with the reference [9]**

Layer Number	Simulated Temperature (°C)	Numerical Results [10] (°C)	Error (%)
1	355.12	356.41	0.13
2	205.18	206.61	0.70
3	470.15	472.15	0.63
4	775.58	777.66	0.26
5	940.58	941.32	0.08
6	1066.42	1065.51	0.09
7	1186.98	1186.44	0.13

8	1216.07	1215.55	0.07
9	1239.44	1238.94	0.04
10	1278.58	1278.55	0.00
11	1317.12	1316.51	0.06

Table 13. Heat flux between different components of the furnace during a full rotation of the disc

Type of Heat Transfer	Value (kJ)	Unit
Heat transfer between lining and environment	15654.66	[kJ]
Heat transfer between gas and coke surface	9072.13	[kJ]
Heat transfer between lining and gas	9072.24	[kJ]
Heat transfer between lining and coke surface	8042.14	[kJ]

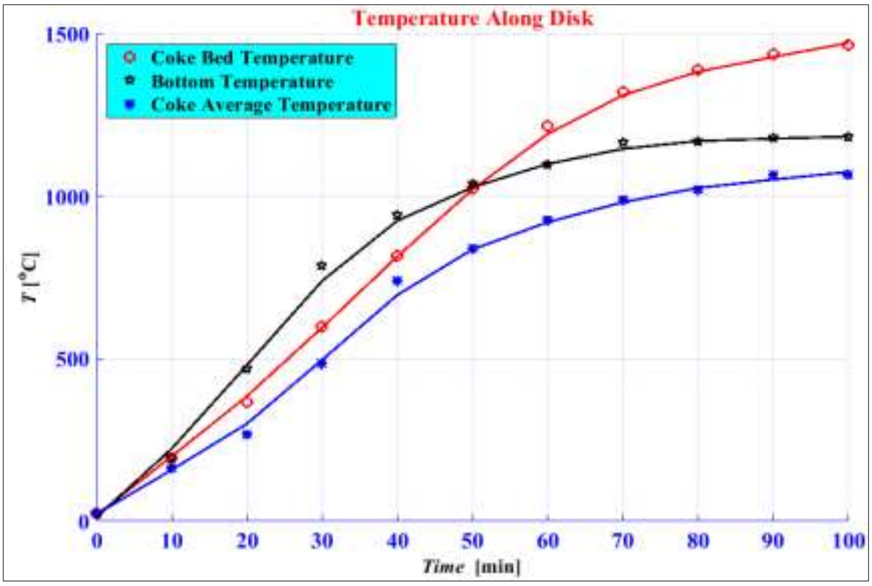

Figure 8. Variations in coke bed temperature, average coke temperature, and lining temperature during the coke retention time in the furnace

It is also evident that the lining temperature increases more sharply at the beginning of the calcination process. This is due to the lining's high heat absorption capacity.

3.1. Thermal Shield Effect

The coke bed temperature rises sharply in the initial layers due to intense radiative heat transfer from the gas phase, governed by Stefan-Boltzmann's law ($Q \propto \epsilon\sigma T^4$). The high gas temperature and emissivity result in rapid energy absorption by the coke surface, causing its temperature to approach the gas temperature quickly. This creates a significant temperature gradient in the first two layers, increasing the risk of cracking and mechanical failure.

Without a thermal shield, the temperature in the first layer rises by nearly 60%, reaching approximately 900°C. This rapid heating induces thermal stresses, leading to particle cracking and disintegration into powder, compromising coke quality. Introducing a thermal shield mitigates this effect, reducing the temperature in the first layer by 8% and in the second layer by 52%. These reductions stabilize the heating process, preventing overheating and improving coke quality.

The shield's effectiveness stems from its high reflectivity (~90%) and low emissivity (~0.1–0.2), redirecting a substantial portion of the radiative energy back to the gas phase. Additionally, increasing the shield's thickness by 20% reduces conductive heat transfer ($q = -k\nabla T$), further stabilising the temperature profile in the initial layers.

Figure 9 illustrates a significant reduction in the coke bed temperature when the thermal shield is applied to the first layer. This stabilizes the initial heating process, minimising the risk of coke particle cracking. The rapid temperature increase observed without the shield is effectively mitigated.

Consequently, at the last layer, the coke bed temperature decreases by 12.9%, the lining temperature by 7.74%, and the coke temperature by 7.33%. While it is possible to place a thermal shield on the second layer and observe its effects, it should be noted that this may significantly increase the likelihood of the coke not being fully calcined, as the furnace must ensure proper coke calcination.

However, the thermal shield on the first layer does not prevent the calcination of the coke, and it reduces the temperatures of the coke bed and the lining, preventing a rapid and sudden temperature rise in these components.

It is important to note that placing a shield on the first layer is merely one approach to mitigating the intense radiative energy. Further research and investigation are necessary to prevent the sudden temperature increase on the coke and lining surfaces. However, what is certain is that placing a shield on the first layer improves coke temperature stability.

Figure 10 demonstrates the effects of placing a thermal shield on the first two layers, showing substantial temperature reductions in the initial layers. However, the lower outlet temperatures indicate a potential risk of incomplete calcination, highlighting the need for optimal shield configuration. Placing the shield on the first two layers significantly reduces the temperature. However, this temperature reduction results in a much lower coke outlet temperature, leading to incomplete calcination and inadequate removal of volatiles from the coke surface.

Figure 11 shows that increasing the thermal shield's thickness by 20% enhances its effectiveness in reducing both radiative and conductive heat transfer. This significantly improves temperature control in the early layers. In Figure 11, the two thermal shield cases are compared. The dashed line represents the use of a thinner shield, while the bold line indicates the use of a thicker shield.

Thus, four scenarios for using the thermal shield were examined in this study:

1. No thermal shield

2. Use of a thin shield on the first path (first layer)

3. Use of a thin shield on the first and second paths (first and second layers)

4. Use of a thick shield on the first and second paths

Figure 12 highlights that different shield configurations directly impact coke bed temperature. Thicker shields or shielding on two layers result in better temperature uniformity in the initial stages.

As shown in Figure 13, thermal shields reduce the lining temperature, protecting the kiln's structural integrity and extending its operational lifespan.

Figure 14 demonstrates that stabilized coke temperatures are achieved with shielding applied to the first layer. However, excessive shielding lowers the final coke temperature, potentially affecting calcination quality.

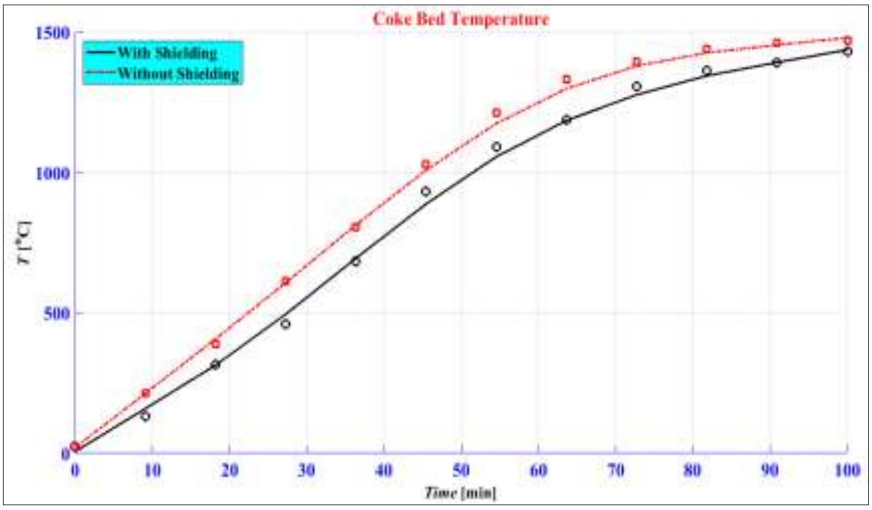

Figure 9. Comparison of coke bed temperature variations with and without the use of a thermal shield

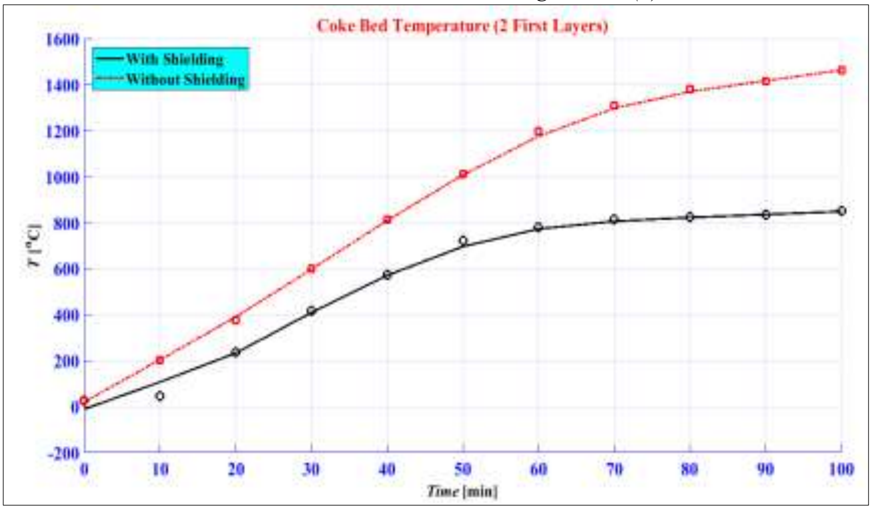

Figure 10. Comparison of coke bed temperature variations with a thermal shield on the first two layers and without a thermal shield

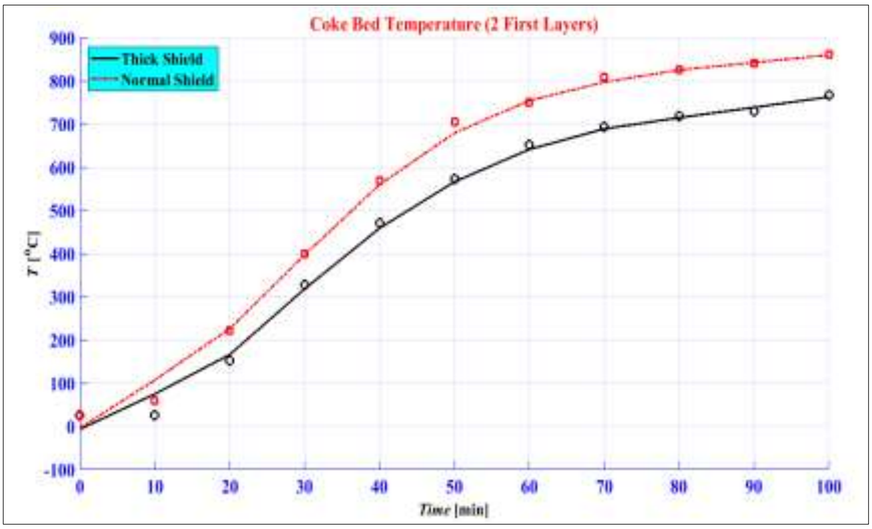

Figure 11. Comparison of different thermal shield configurations on coke bed temperature

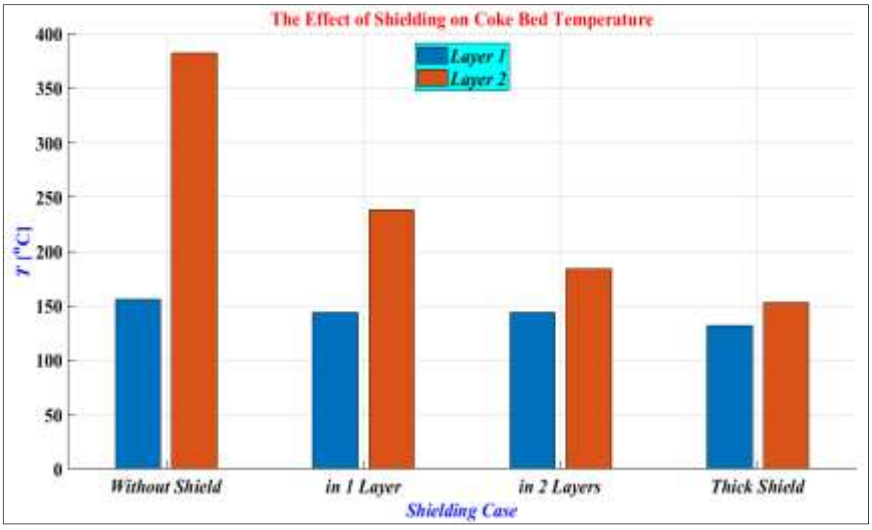

Figure 12. Effect of different thermal shield configurations on the coke bed temperature at the end of the first two layers

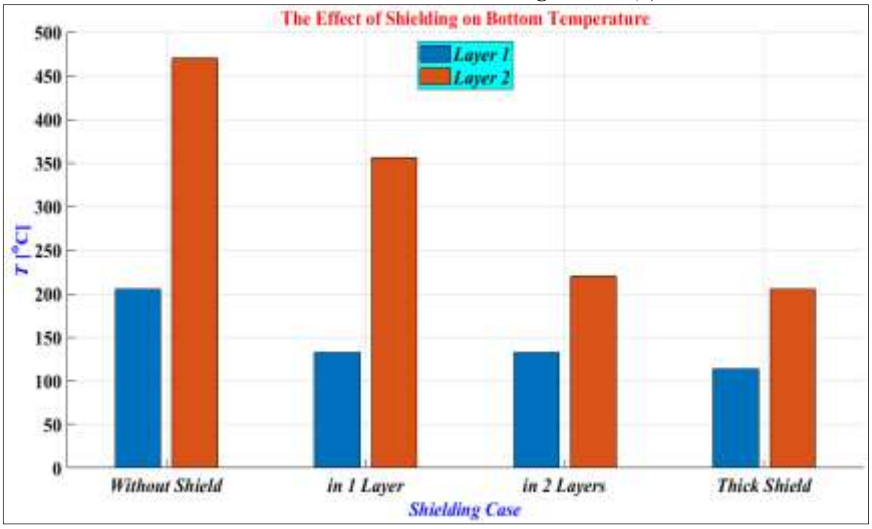

Figure 13. Effect of different thermal shield configurations on the lining temperature at the end of the first two layers

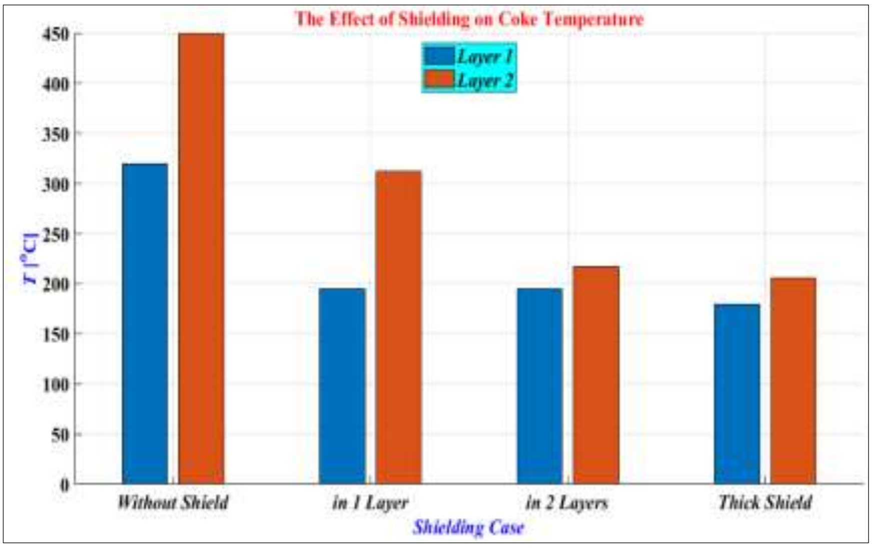

Figure 14. Effect of different thermal shield configurations on the coke temperature at the end of the first two layers

3.2. Coke Quality

The retention time of coke in the furnace is a critical parameter for determining its quality. Generally, the better the calcination process is performed, the higher the quality of the output coke. This section discusses the effect of coke retention time in the furnace on coke density, porosity, and crystal size.

Figure 15 shows that as the retention time increases, more volatile substances are removed from the coke, leading to higher purity and, consequently, higher coke density.

Figure 15. Effect of retention time on coke density

Figure 16 illustrates the porosity percentage. As shown, increasing the retention time causes the coke to dry and moisture to be removed, which reduces the pores in the coke structure that could otherwise trap air or humidity.

The smaller the crystal size of the coke, the closer the constituent particles of a coke mass are to each other, resulting in denser coke (Figure 17). This indicates that there is less space for air, moisture, or other volatile substances to occupy. Therefore, reducing the crystal size of coke improves its quality and purity.

Figure 16. Effect of retention time on apparent porosity

Figure 17. Effect of retention time on crystal size

3.3. Comparative Analysis with Other Heat Flow Control Methods

1. Thermal management in rotary kilns has been the subject of extensive research, with several methods proposed to optimise heat transfer and improve process efficiency. The following compares the thermal shield approach with other commonly used techniques:

2. Preheating green coke before it enters the kiln reduces the temperature differential, leading to more gradual heating. While effective in improving coke quality, this method requires additional infrastructure, increasing capital and operational costs. The thermal shield offers a more straightforward and more cost-effective alternative with comparable benefits in temperature control.

3. Techniques such as altering kiln geometry, introducing baffles, or optimising rotational speeds have been explored. Although these approaches enhance heat transfer, they often require significant modifications to existing kilns, resulting in downtime and increased costs. The thermal shield can be retrofitted with minimal disruption and investment.

4. High-emissivity coatings on refractory linings improve heat transfer uniformity. However, these coatings have limited durability under prolonged high-temperature exposure, leading to frequent reapplications. In contrast, the aluminum shield demonstrates consistent performance and lower maintenance requirements.

5. Adjusting the flow of hot gases within the kiln is another method to manage heat distribution. While this approach can be practical, it depends heavily on precise control systems and regular monitoring, which may not be feasible in all industrial settings. The thermal shield provides a passive, low-maintenance solution.

6. The thermal shield enhances energy efficiency by reducing unnecessary heat losses in the rotary kiln. By redirecting radiative energy to the gas phase, the shield concentrates energy where it is most effective for calcination. This improves the utilisation of heat energy, reducing the need for excessive fuel input. Moreover, the shield stabilizes temperature gradients, ensuring a consistent heating process that minimizes overcompensation through increased fuel supply. This not only reduces the operational carbon footprint but also results in significant cost savings for industrial operations. Insulating layers reduce heat losses but may also hinder efficient heat transfer to the coke bed. The thermal shield balances these factors by selectively reducing heat flux to the initial layers without compromising overall kiln efficiency.

3.4. Sensitivity Analysis

To strengthen the results, a sensitivity analysis was performed to evaluate the impact of key variables on the coke bed temperature and heat transfer dynamics. The parameters studied included the emissivity of the materials and the thermal conductivity of the coke bed.

3.4.1. Impact of Emissivity:

The emissivity of the coke bed varied from 0.7 to 0.9. A higher emissivity increased radiative heat transfer, raising the coke bed temperature by up to 5% in the initial layers, while lower emissivity reduced this temperature rise by 4%.

- The emissivity of the refractory lining had a negligible effect on the coke bed temperature but influenced the lining temperature by ±3%.

3.4.2. Impact of Thermal Conductivity:

The thermal shield effectively reduces temperature gradients within the coke bed, promoting the stability of the calcination process. Without the shield, steep gradients cause thermomechanical stresses, weakening the structural integrity of coke particles and leading to quality degradation.

The shield's stabilization results from its ability to distribute heat evenly across the layers. By minimising radiative and conductive heat fluxes in the initial layers, the shield ensures more uniform heating, reducing the risk of thermal stresses. This effect is particularly pronounced in the second and third layers, where the shield's influence extends beyond the immediate vicinity of the gas phase.

These stabilized gradients enhance the calcination process by improving coke density and reducing pore formation, critical factors for downstream applications such as aluminum anode production.

- The thermal conductivity of the coke bed was adjusted by ±20% from its nominal values. Increasing the thermal conductivity enhanced the heat transfer within the coke bed, reducing temperature gradients and stabilizing the temperature profile, especially in the middle layers. Conversely, lower conductivity intensified thermal gradients, leading to potential overheating in the upper layers.

3.4.3. Other Variables:

- A marginal effect (<2%) was observed for variations in gas thermal conductivity, indicating the dominant role of radiative heat transfer.

3.5. Practical and Industrial Implications

The findings demonstrate the thermal shield's practicality and viability for industrial applications. Its lightweight and modular design allows seamless integration into existing rotary kilns without requiring extensive modifications. The shield's cost-effectiveness and dual role in enhancing product quality and reducing structural degradation make it a valuable addition to industrial calcination processes.

From an operational perspective, the shield's ability to stabilize temperatures and reduce thermal stresses translates to lower maintenance costs and extended kiln lifespan. These benefits align with industry goals of improving energy efficiency, reducing carbon emissions, and optimising product quality.

4. Conclusion

In this study, a simple one-dimensional thermal model was developed to analyse the calcination process of coke. Heat transfer between the various components of the furnace was examined, and the influence of each component on the calcination process in rotary disc furnaces was evaluated. A creative idea was implemented to reduce radiative heat flux to the coke bed. Specifically, a thermal shield was utilized in the first coke layers to lower the heat flux to the coke bed. The thermal shield was applied in different configurations, including:

1. No thermal shield,
2. A thin thermal shield on the first layer,
3. A thin thermal shield on the first two layers and,
4. A thick thermal shield on the first two layers.

The coke's retention time in the furnace was set to 100 minutes. The results indicated that the calcination process over 100 minutes was sufficiently effective, with the final coke temperature reaching a level that preserved its desired properties and quality.

The results of this study demonstrate that thermal shields effectively reduce the coke bed temperature in the first two layers by up to 8% and 52%, respectively. These findings are consistent with the temperature control principles discussed by Modest [15], where emissivity and reflectivity play crucial roles in heat flux reduction.

Compared to the work of Kocaefe et al. [3], which focused on the influence of heating rates, this study provides a more targeted solution to address rapid temperature rises in specific layers. Similarly, while Martins et al. [9] emphasized the importance of kiln rotation speed, this work highlights the complementary role of thermal shielding in achieving uniform temperature distribution.

Using a thin thermal shield on the first layer did not significantly reduce the coke outlet temperature, ensuring good coke quality. However, using two layers of shielding or a thick thermal shield, while improving the temperature variations in the initial layers, led to a significant reduction in the coke outlet temperature, resulting in a severe decrease in coke quality.

5. Nomenclature

Symbol	Definition	Unit
Q	Radiative heat flux	W/m^2
ϵ	Emissivity	-
σ	Stefan-Boltzmann constant (5.67×10^{-8})	$W/m^2\ K^4$
T	Temperature	K
q	Conductive heat flux	W/m^2
k	Thermal conductivity	W/m K
∇T	Temperature gradient	K/m
R	Thermal resistance	K/W
L	Thickness of material	m
C_p	Specific heat capacity	J/kg K
ρ	Density	kg/m^3
h	Convective heat transfer coefficient	$W/m^2\ K$
Nu	Nusselt number	-

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