

Article

Dynamic Simulation of Heat Distribution and Losses in Cement Kilns for Sustainable Energy Consumption in Cement Production

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Abstract: Sustainable energy consumption in cement production involves practises and strategies aimed at reducing energy use and minimising environmental impact. The efficiency of a cement kiln is dependent on the kiln design, fuel type, and operating temperature. In this study, a dynamic simulation analysis is used to investigate heat losses and distribution within kilns with the aim of improving energy efficiency in cement production. This study used Computational Fluid Dynamics (CFD) with Conjugate Heat Transfer, Turbulent Flow, and the Realisable $k-\epsilon$ turbulence model to simulate heat transfer within the refractory and wall systems of the kiln, evaluate the effectiveness of these systems in managing heat losses, and establish the relationship between the heat transfer coefficient (HTC) and the velocities of solid and gas phases. The simulation results indicate that a temperature gradient from the kiln's interior to its exterior is highly dependent on the effectiveness of refractory lining in absorbing and reducing heat transfer to the outer walls. The results also confirm that different thermal profiles exist for clinker and fuel gases, with clinker temperatures consistently peaking at approximately 1450 °C, an essential condition for optimal cement-phase formation. The results also indicate that phase velocities significantly influence heat absorption and transfer. Lower velocities, such as 0.2 m/s, lead to increased heat absorption, but also elevate heat losses due to prolonged exposure. The relationship between the heat transfer coefficient (HTC) and the velocities of solid and gas phases also indicates that higher velocities improve HTC and enhance overall heat transfer efficiency, reducing energy demand.



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Keywords: computational fluid dynamics; energy efficiency; heat transfer; process simulation

1. Introduction

Cement production is one of the largest direct industrial sources of greenhouse gas (GHG) emissions, contributing up to 8% of global CO₂ emissions, largely due to the high energy required, mainly from fossil fuels and other associated pollutants [1,2]. The cement sector plays an important role in infrastructure and economic development, but its contribution to climate change is a huge challenge. The increase in urbanisation and industrialisation has led to increased demands for cement, thereby increasing the urgency to adopt sustainable practises for cement production [3]. During production, a mixture of calcium carbonate and alumino-silicate materials, such as clay, are heated to a temperature of approximately 1450 °C to calcinate raw materials and change them into clinker [4].

This process is extremely energy-intensive, and accounts for around 85% of the total energy required to produce cement [5]. For limestone to break down into calcium oxide (CaO) and carbon dioxide (CO₂), a high temperature is required. At the same time, other oxides in the mixture also go through processes which create major phases like tricalcium silicate and minor phases like tricalcium aluminate and dicalcium silicate (2CaO·SiO₂) [5,6]. Nevertheless, this phase transformation is a highly energy-consuming process and leads to significant heat loss due to radiation and convection from kiln surfaces. These losses can be around 15–16% of the total energy input, reflecting the process inefficiencies [6,7].

Modern cement production techniques have evolved to address environmental concerns and improve efficiency. Recent studies [8–12] have explored various strategies to mitigate these inefficiencies and reduce the carbon footprint of cement production. Innovations in alternative fuels, such as bio-derived fuels, and the adoption of advanced material technologies like calcined clay [11], have shown potential in reducing energy consumption and emissions. The development and implementation of carbon capture, utilisation, and storage technologies are also being extensively researched as viable options to significantly lower CO₂ emissions from cement kilns.

The energy requirement for the clinker formation process is estimated to be around 60% efficient, where 5.74% of the total energy loss is not identified [12]. This reflects the fact that much of the energy input is not efficiently used for production, and hence is used in clinker. Losses happen through the kiln shell, hot flue gases, and cooler stacks. The shell kiln is individually responsible for 11.3% of the total losses, mainly involving heat being lost through radiation and convection [13,14]. Other energy losses during clinker production are caused by the hot flue gases, which are expelled at high temperatures and contain substantial thermal energy. These gases can carry away approximately 35–40% of the total process heat loss [15], depending on the efficiency of the kiln operation and the heat recovery systems in place. During the clinker cooling process, up to 10–15% of the total energy input to the kiln can be lost [16]. This heat is released into the atmosphere through cooler stacks. Poorly performing refractory lining can account for about 5–10% of total energy losses [17]. Additional heat losses occur due to dust and clinker discharge, contributing to about 20–30% of the heat input loss [18]. Addressing these issues through improved heat recovery systems, better cooling technologies, and enhanced refractory materials can significantly reduce energy losses and increase the overall efficiency of the cement production process.

Heat transfer within the kiln involves an interplay of conduction, convection, and radiation, which are crucially interrelated throughout the length of the kiln [19]. The process can be divided into several stages, including drying, preheating, and sintering, each contributing differently to heat generation and loss. The sintering zone, in particular, is critical due to its high-temperature requirements, where temperatures can exceed 2100 °C [20]. The refractory lining is also crucial in transferring heat from the hot inner surface of the refractory to its colder outer surface [21]. The rate of conduction is determined by the thermal conductivity of the refractory material, which regulates how easily it conducts heat [22,23]. Inside a kiln, a transfer mechanism occurs when hot gases transport heat to the inner surface of the refractory lining by convection, with the velocity and temperature of these gases having a substantial impact on the rate of convective heat transfer [24]. The heated exterior surface of the kiln shell radiates heat into the surrounding environment, with the rate of radiative heat loss determined by the temperature of the kiln walls and emissivity, which determines how well it emits radiation [25,26].

To address these inefficiencies, recent studies [27,28] have explored improving kiln design, operational techniques, and the use of alternative fuels as imperative to enhancing energy efficiency. Preheating raw materials before they enter the kiln can considerably

reduce the energy required for clinker production. One critical factor that influences the energy efficiency and quality of clinker is the design of the burner. The burner generates the heat needed to calcine raw materials and, therefore, the dynamics of heat distribution within the kiln are greatly affected by its design, which is often overlooked in studies that optimise kiln efficiency. Addressing this important aspect is essential for a comprehensive approach to improving energy efficiency in clinker production [27]. Advanced systems like cyclone preheaters enhance energy efficiency by recovering heat from exhaust gases to preheat the incoming raw materials, thereby reducing the energy demand during calcination [28]. In addition to preheating, modern control systems and high-efficiency materials have been used for improving kiln energy efficiency.

Advanced process control systems have been used to monitor and adjust process parameters in real-time [29], ensuring the kiln runs effectively. In addition to minimising energy loss, process control systems aid in maintaining uniformity of clinker quality [30]. Computational tools, particularly Computational Fluid Dynamics (CFD), have also emerged as useful methods for modelling and optimising heat distribution and losses in cement kilns. CFD models can predict the temperature distributions of the kiln, heat transfer into the clinker, and heat loss from the refractory or kilns to the ambient air by elucidating such thermal processes [31–36]. Due to these very significant contributions, CFD models have also been used in a few studies which employed CFD software like COMSOL Multiphysics to analyse heat transfer mechanisms during clinker production.

Despite recent advancements in kiln technology, there are still significant gaps in understanding the heat dynamics involved in clinker formation and their impact on refractory linings and the overall kiln wall systems. Research gaps such as incomplete characterisation of the thermophysical properties involved in heat flow during clinker formation, a lack of quantitative data on the interactions between thermal gradients and refractory linings, and limited understanding of how the combined heat and mass transfer processes affect overall kiln performance and energy consumption, highlight the need for a comprehensive investigation into how these thermal interactions affect kiln performance and energy consumption. In this study, a combination of Conjugate Heat Transfer, Turbulent Flow, and the Realisable $k-\epsilon$ turbulence model was used to simulate the heat interactions in solid and fluid phases under turbulent conditions. By systematically integrating CFD modelling, this study identifies inefficiencies in the heat transfer processes and proposes solutions that enhance overall sustainability in cement production.

2. Methodology

This section describes the approach used for data collection. It also explains the concept and procedure used in the dynamic simulation of heat losses and distribution through the refractory and the walls of the kiln system.

2.1. Process Description

Figure 1 shows the cement production process at a semi-automated factory in Zambia. The process begins with raw materials, primarily limestone, being proportioned and ground, which requires mechanical energy. The preheating stage uses hot gases from the kiln to reduce energy consumption before the material enters the kiln, where significant energy, primarily thermal energy, is consumed to attain high temperatures (about 1450 °C) and generate clinker. This is the most energy-intensive stage, as well as the source of the majority of energy losses, which are caused by heat dissipation. Following the kiln, the hot clinker is rapidly cooled in the clinker cooler, which results in additional energy losses in the form of heat emitted into the environment. Recycling heat from the kiln back into the preheating stage helps to reduce overall energy use. The plant has two rotary kilns,

each lined with refractory materials to withstand high temperatures, and is inclined at a 3° to 3.5° angle to facilitate material flow. It measures 3.8 m in diameter and 50 m in length, with a daily capacity of 3000 tons of clinker. The preheating stage uses cyclone-type preheaters to efficiently elevate the temperature of the raw materials before they reach the kiln, optimising the calcination process and saving energy. Specific fuel consumption for this kiln is estimated at 21 kg of coal per ton of clinker produced.

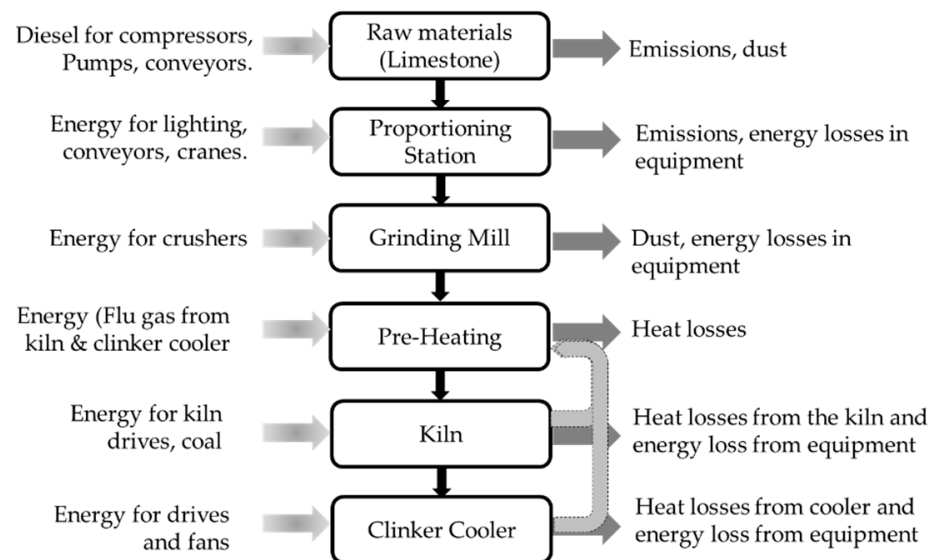


Figure 1. Process flow of a typical dry process cement production plant.

Operational variables significantly influence heat losses during the clinker formation process. Efficient grinding and precise proportioning of raw materials are essential for reducing energy consumption in kilns. The efficiency of cyclone-type preheaters during the preheating stage is crucial for minimising the thermal energy required for clinker formation [32], as these preheaters effectively raise the temperature of raw materials using recycled kiln gases. While the kiln is in operation, factors such as the kiln's rotational speed and angle of inclination affect heat efficiency. Managing these variables can reduce heat loss and enhance thermal energy retention. Furthermore, improving the heat recovery efficiency in the clinker cooler can significantly lower the heat discharged into the environment, thus minimising overall energy losses.

2.2. Data Collection

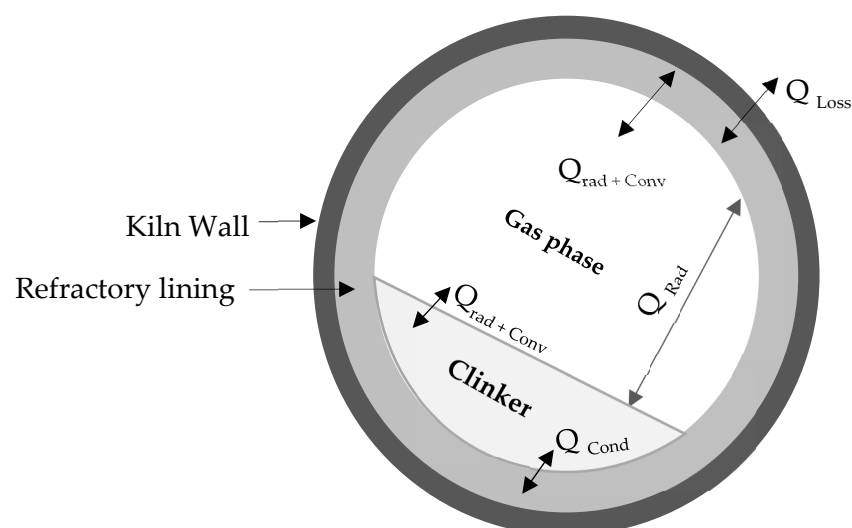
Table 1 shows the process data obtained from the semi-automated plant in Zambia. The data indicate that the kiln has a diameter of 3.8 m and a length of 50 m, operating in three 8 h shifts from Monday to Saturday. The flue gas temperatures at the kiln exit range between 900 and 1000 °C, and the clinker discharge temperature varies from 850 to 950 °C. The table also reveals that estimates are required for the thermal conductivity of both the refractory material (alumino-silicate fireclay bricks) and the kiln wall, which are essential for studying heat retention and loss within the kiln. In terms of energy consumption, the plant recorded usage of 7073 MWh of electricity and 6810 tons of coal for August 2021, highlighting the significant energy demands of cement production. Furthermore, energy loss estimates are noted, particularly concerning heat loss from the kiln shell, pointing to potential inefficiencies that need precise quantification.

Table 1. Operating parameters and conditions for the rotary kiln.

Category	Parameter	Details or Value
Kiln Specifications	Diameter (m)	3.8
	Inner Refractory Diameter (m)	3.2
	Speed of Rotation (rpm)	5.2
	Wall Thickness (m)	0.15
	Length	50
	Flue Gas Temperature at Kiln Exit (°C)	900–1000
	Clinker Discharge Temperature (°C)	850–950
Energy Consumption	Electricity (kWh) as of August 2021	7,073,039
	Coal (tons) as of August 2021	6810
Operational Challenges	Deterioration of Refractory Materials	Effects thermal efficiency
	Leaks in Kiln System	Leak rate needs specification
	Excess Air Ratio	Approximately 10–12%, effects combustion efficiency

2.3. Dynamic Simulation Modelling

Heat transfer between the solid bed and the internal wall was considered in this simulation as critical for describing the overall heat transfer efficiency. The simulation of heat transfer is primarily characterised by three key mechanisms: conduction through the gas film that exists between the wall and the bed, direct conduction through solid–wall contact, and advective heat transfer occurring near the edges of the bed, as shown in Figure 2. Convective heat transfer in rotary kilns was simulated using gas and solid mass flow, rotational speed, particle size, and temperature. The reaction zone within a cement kiln consists of a mixture of gases produced from fuel combustion and chemical reactions taking place inside the kiln. For this study, it was assumed that the gas is either dry air or a product of the complete combustion of natural gas in dry air. To accurately assess radiative heat transfer within the kiln, the emissive and absorptive characteristics of these gas mixtures were assessed.

**Figure 2.** Schematic heat and mass flow in the cross-section of a kiln segment.

The parameters used in the simulations were established through a combination of actual data collection from the plant, literature reviews, and the material library available in CFD-COMSOL 6.3. The thermal properties of the kiln wall, made of carbon steel, and the refractory material, which is composed of firebrick clay, were obtained from COMSOL's material library. The reaction rate constants (K1–K5) for the essential clinker-forming reactions were determined by considering the kinetics of these reactions, as outlined in studies [33–35]. For heat transfer parameters, including the heat transfer coefficient, empirical correlations were derived from scientific studies [36–39]. The volumetric heat source was informed by burner specifications and was used to measure temperatures during operation. The feed mass fractions, and initial compositions of raw materials and fuels, were also based on data gathered from plant operations.

2.3.1. Model Formulation

A dynamic simulation of heat distribution was performed on the refractory material and the kiln wall. The Quadratic Lagrange method was used for temperature discretisation, with the reference temperature set at 1450 °C, which corresponds to the clinker production temperature.

i. Heat transfer through the kiln wall and refractory.

The heat transfer through the refractory and the kiln wall was modelled using Equation (1).

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{ted} \quad (1)$$

where $\rho C_p \mathbf{u} \cdot \nabla T$ is the conduction transport of heat within the solid;

ρ is the density of the material (firebrick clay);

C_p is the heat capacity at constant pressure derived from the material properties;

$\mathbf{u}$ is the velocity vector representing the fluid movement which influences convective heat transfer;

$\nabla \cdot \mathbf{q}$ is the rate at which heat flows through the materials;

Q is the volumetric heat source;

Q_{ted} is the heat generated due to thermal expansion.

The heat flux through the refractory and the kiln follow Fourier's law, and can be defined as Equation (2)

$$\mathbf{q} = -k \nabla T \quad (2)$$

where

k is the thermal conductivity of materials;

∇T is the temperature gradient indicating how temperature changes across the solid materials.

ii. Heat transfer through the raw mix and fuel.

The heat conduction for a defined refractory wall can be expressed using Fourier's law, as shown in Equation (3)

$$Q_{cond} = -k \cdot A \cdot \frac{\Delta T}{d} \quad (3)$$

where

A is the surface area of the kiln wall (m²);

d is the thickness of the refractory layer.

The rate of heat transfer in gases within the kiln is measured through convection and can be described as Equation (4)

$$Q_{conv} = h.A.(T_{surface} - T_{gases}) \quad (4)$$

where h is the convective heat transfer coefficient (HTC) for gas inside the kiln ($W/m^2 \cdot ^\circ C$);

A is the surface area of the kiln wall;

$T_{surface}$ is the temperature of the kiln wall;

T_{gases} is the temperature of the gas inside the kiln.

The time-dependent equation shown in Equation (5) describes the heat transfer through the raw mix and the fuel from the burner.

$$d_z \rho C_P \frac{\partial T}{\partial t} + d_z \rho C_P u \nabla T + \nabla q = d_z Q + q_0 + d_z Q_{ted} \quad (5)$$

The primary mode of heat transfer is radiation, where the velocity u may be zero or insignificant. The heat storage is described by $\rho C_P \frac{\partial T}{\partial t}$, which represents the material's thermal inertia.

The terms $d_z \rho C_P u \cdot \nabla T$ represent the heat due to fluid motion, which explains the modelling of how fluid flow influences the temperature distribution. The direction of heat transfer along the axis is represented by d_z

iii. Turbulence flow and dissipation rate

The Realisable $k-\epsilon$ model was used to simulate turbulent heat flow and improve prediction accuracy in such settings. Equation (6) was used to define the revolving heat flows near the kiln walls and across its axis.

$$\frac{\partial(\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \epsilon u) = \nabla \cdot \left[\left(u + \frac{\mu T}{\sigma_\epsilon} \right) \nabla \epsilon \right] + C_1 \rho S_\epsilon - C_2 \rho \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} \quad (6)$$

where

σ_ϵ is the turbulent Prandtl number ϵ ;

$C_1 C_2$ are the empirical constants;

S is the magnitude of the strain rate.

The turbulent viscosity can be described by Equation (7), which relates the kinetic energy to its dissipation rate.

$$\mu_T = \rho C_\mu \frac{k^2}{\epsilon} \quad (7)$$

where μ_T is the turbulent viscosity, k is the turbulent kinetics, ϵ is the dissipation rate, and C_μ is the empirical coefficient.

iv. Kinetics of clinker formation in the bed

The reaction engineering interface was selected to simulate the clinker formation reaction. The reactor engineering model in a batch reactor model set up in COMSOL Multiphysics, specifically under the Reaction Engineering interface. The model followed Equation (8)

$$V_r \frac{dC_i}{dt} = V_r R_i \quad (8)$$

which represents the time rate of change in chemical concentration C_i in the kiln volume V_r as a function of reaction rate R_i . The feed mass fraction used is shown in Table 2.

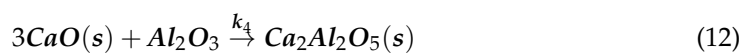
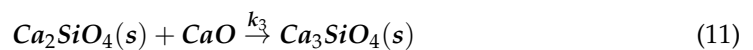
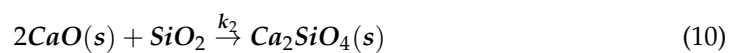
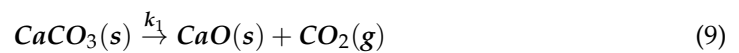
The simulation of clinker formation was performed using initial compositions for the raw materials and fuel mixtures, comprising components and their proportions. Key

chemical reactions modelled in this simulation included the decomposition of calcium carbonate, the formation of dicalcium silicate, tricalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. Reaction kinetics were represented by specific rate constants for each reaction K1 to K5, as shown in Equations (9) and (13), respectively, which were incorporated into a system of differential equations that described the mass balance of each chemical species. The rate equations were based on the assumption that the reaction rates are proportional to the concentrations of the reactants, following first-order kinetics. The main assumptions of this model included ideal mixing within the reactor, a constant temperature throughout the reaction process, and the absence of side reactions or losses other than those specifically defined.

Table 2. Chemical composition of the raw mix and fuel.

Raw Mixture (wt.%)		Fuel Mixture (wt.%)	
CaCO ₃	70%	CO	42
SiO ₂	23%	CO ₂	26
Al ₂ O ₃	5%	N ₂	3.5
Fe ₂ O ₃	1.5	H ₂	21
MgO	0.5%	CH ₄	3.7
Loss of Ignition	2%	H ₂ O	3.2
		H ₂ S	0.6

The chemical reactions involved in clinker formation are assumed and described in Equations (9)–(13).



The rate of reactions for each reaction as calculated using Equation (14).

$$r = yfa_k \quad (14)$$

where yfa_k quantifies the proportion of the total mass of the mixture that is made up by species k .

Table 3 shows the mass transfer and coupling parameters for the reaction engineering interface and the Transport of Concentrated Species interface, which were used for simulating clinker formation kinetics.

Table 4 shows the boundary conditions and parameters used in the design of the kiln, including material properties and thermal boundary conditions for a rotary kiln system, such as solids and air flow rates and coal characteristics. Table 4 also shows thermal conductivities and heat fluxes that influence kiln operation.

Table 3. Mass transfer and coupling parameters for the reaction engineering interface.

Parameter	Symbol/Value	Units	Reference
Pre-exponential factors	$k_1 - k_5$	s^{-1}	Multi-step reaction adopted from the literature
Activation energies	$E_{a,1} - E_{a,5}$	kJ/mol	Arrhenius parameters adopted from the literature
Reactor volume	V_r	m^3	Defined by kiln geometry/assumed reaction zone
Density of the mix	ρ_{mix}	kg/m^3	1500 kg/m^3
Density of gas	ρ_{gas}	kg/m^3	Calculated from equation of state at kiln conditions
Thermal conductivity (solid)	k_{solid}	$W \cdot (m \cdot ^\circ C)$	Temperature-dependent property functions from CFD material library.
Thermal conductivity (kiln shell)	k_{shell}	$W \cdot (m \cdot ^\circ C)$	Temperature-dependent property functions from CFD material library
Heat capacity (solid)	Cp_{solid}	$J/(kg \cdot ^\circ C)$	Temperature-dependent property functions from CFD material library
Heat capacity (gas)	Cp_{gas}	$J/(kg \cdot ^\circ C)$	Temperature-dependent property functions from CFD material library
Convective heat transfer coefficient	h	$W/(m^2 \cdot ^\circ C)$	For gas–solid convection
Diffusion coefficient (gas)	D_k	m^2/s	3×10^{-3} , adopted from the literature
Initial temperature	T_0	K	A preheated value from process data
Operating pressure	ρ_0	Pa	101,325 Pa, adopted from the literature

Table 4. Boundary conditions and parameters for kiln design.

No.	Description	Variable	Value or Condition
1	Solids inflow	Kiln solids inflow	37.80 kg/s
2	Secondary air flow	Secondary air	12.46 kg/s
3	Axial air flow	Axial air	1.17 kg/s
4	Coal air flow	Coal air	0.943 kg/s
5	Calorific value	Caloric value	6200 kcal/kg coal
6	Particle size	Coal particle size	120 μm
7	Kiln wall thermal conductivity	Kiln wall	45 $W/(m \cdot ^\circ C)$
8	Refractory thermal Conductivity	Refractory	0.05 $W/(m \cdot ^\circ C)$
9	External conditions	Kiln wall heat flux	18 $W/(m^2 \cdot ^\circ C)$
10	Internal conditions	Refractory wall flux	60 $W/(m^2 \cdot ^\circ C)$

2.3.2. Geometry

Figure 3 shows a simplified diagram of a rotary kiln in a cylindrical structure with a length of 50 m. A burner is installed at the kiln's left end, with a fuel inlet into the kiln. The kiln is inclined at 3° to support the passage of the material from the higher end to the lower end through gravity and rotational motion.

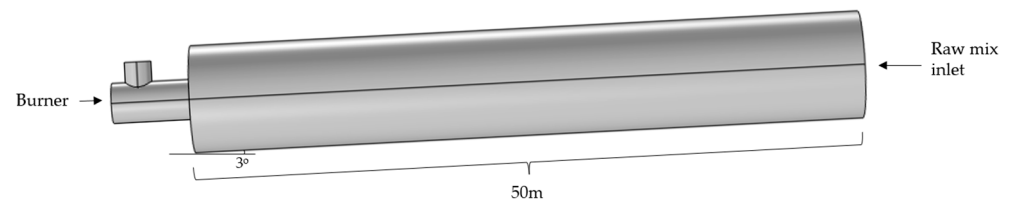


Figure 3. Geometry of the kiln.

2.3.3. Meshing

A mesh-dependence study was conducted, and the mesh was appropriately refined to balance detail and computational efficiency. Figure 4 was designed as a physics-controlled mesh suited for heat transfer analysis in materials. The element size was set to extra fine in critical areas such as the burner and transitioned to coarser grids towards the middle of the kiln, which enhanced the accuracy of thermal gradient analysis while optimising processing resources. A tetrahedral mesh was used for the heat transfer simulation. A total of 270,250 cells in the radial directions were used to simulate the entire kiln, using a curvature-based mesh. Figure 4b shows the wall meshing and the refractory, and Figure 4c indicates the mesh along the kiln axial. The mesh was finely tuned with an element size as small as 1 mm in critical areas, such as around the burner, to accurately capture complex thermal gradients. In the middle sections of the kiln, where less variability is expected, coarser grids of approximately 5–10 mm were utilised. This strategic gradation ensured that about 30% of the total 270,250 cells (approximately 81,075 cells) were concentrated in the detailed regions near critical interfaces, while the remaining 70% (around 189,175 cells) were allocated to the broader, less critical areas. The mesh quality metrics were optimised, achieving an average aspect ratio of around 3, a skewness below 0.4, and orthogonality deviations within 10 °C from the ideal. These adjustments enhanced the accuracy of the simulation and computational efficiency, effectively capturing all relevant phenomena, including fluid flow and chemical reactions within the kiln.

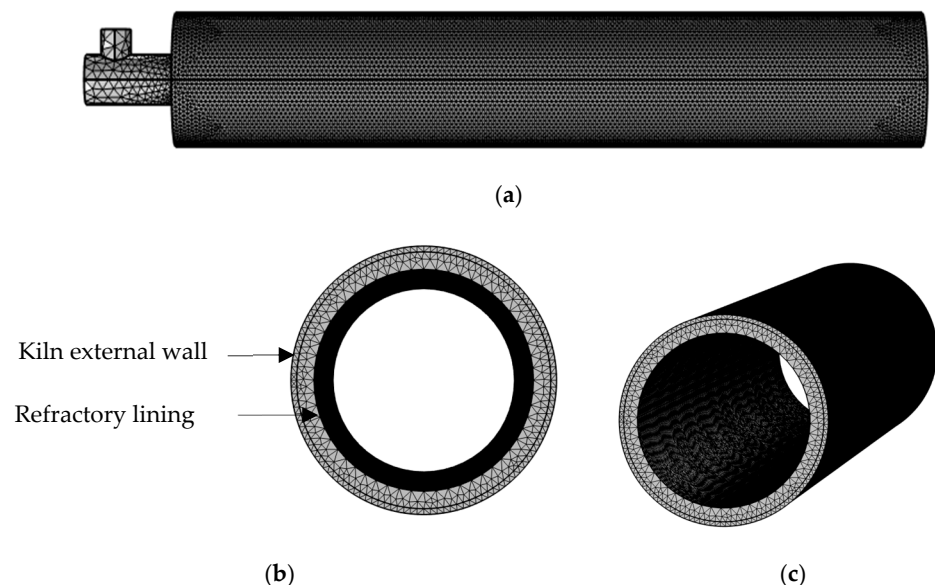


Figure 4. Meshing for (a) horizontal kiln design (b) cross-sectional of the kiln shell (c) Cross-sectional for kiln's layered structure.

The mesh incorporated both the solid structures as well as fluid regions for modelling heat transfer interactions between gas phases and walls. This comprehensive approach ensured that all relevant phenomena, including fluid flow and chemical reactions occurring

within the kiln, were effectively captured, thereby enhancing the reliability of the analysis and the understanding of heat transfer.

2.3.4. Boundary Conditions

Several crucial boundary conditions were taken into account to accurately describe the behaviour of the clinker kiln in the simulations that were carried out using COMSOL Multiphysics 6.3 in conjunction with User Defined Functions in CFD software. These include the specification of uniform gas velocity for the secondary air inflow, originating from the clinker cooler, along the kiln axis as an inflow boundary condition. It was also assumed that fuel particles, upon colliding with the kiln wall or clinker bed, remain fixed at the impact point, with the ash fraction from the fuel transferring directly to the kiln segment at the point of contact. Furthermore, no further interaction between these fuel particles and the clinker bed was considered beyond this transfer. According to the process data obtained, the kiln wall was made of carbon steel and had a thermal conductivity of $45 \text{ W}/(\text{m}\cdot\text{K})$. Its thermodynamic parameters were obtained from the material library within COMSOL software to ensure a precise heat conduction response. The refractory material used was firebrick clay (SiO_2 –62%, Al_2O_3 –35%, MgO 3%) with a thermal conductivity of $0.05 \text{ W}/(\text{m}\cdot^\circ\text{C})$. The heat input from the burner was assumed to be a volumetric heat source within the combustion zone at a temperature of 1449.85°C . The heat flux of the kiln wall was assumed to be conductive, with a heat transfer coefficient of $18 \text{ W}/(\text{m}^2\cdot^\circ\text{C})$, and an external temperature of 40°C was assumed. Table 4 shows the boundary conditions that were used to simulate heat transfer in the kiln system.

3. Results

This section presents the results of dynamic simulations that investigated heat transfer through the kiln's refractory lining and wall. The results also show how differences in clinker velocity and the velocity of solid and gas phases affect heat distribution and transfer efficiency. This section also discusses the thermal dynamics of clinker formation and the behaviour of distinct mineral phases at high temperatures, providing crucial knowledge on improving clinker quality and energy efficiency in the production of cement.

i. Simulation of the refractory and the kiln wall

The results for the dynamic simulation of heat transfer and distribution through the refractory lining and the kiln wall are shown in Figure 5. The figures indicate that the temperature decreases from the hottest regions near the inner surface of the refractory regions to the outer layers of the kiln wall. This suggests that the internal structure of the kiln, when in contact with high-temperature gases or materials, experiences intense heat that gradually decreases as it travels through the insulating refractory and reaches the outside carbon steel wall. The refractory lining effectively absorbs and reduces high temperatures, hence reducing the heat transfer to the exterior wall. The consistent distribution of heat throughout the kiln wall also implies that both the refractory and kiln walls have the expected thermal conductivity qualities.

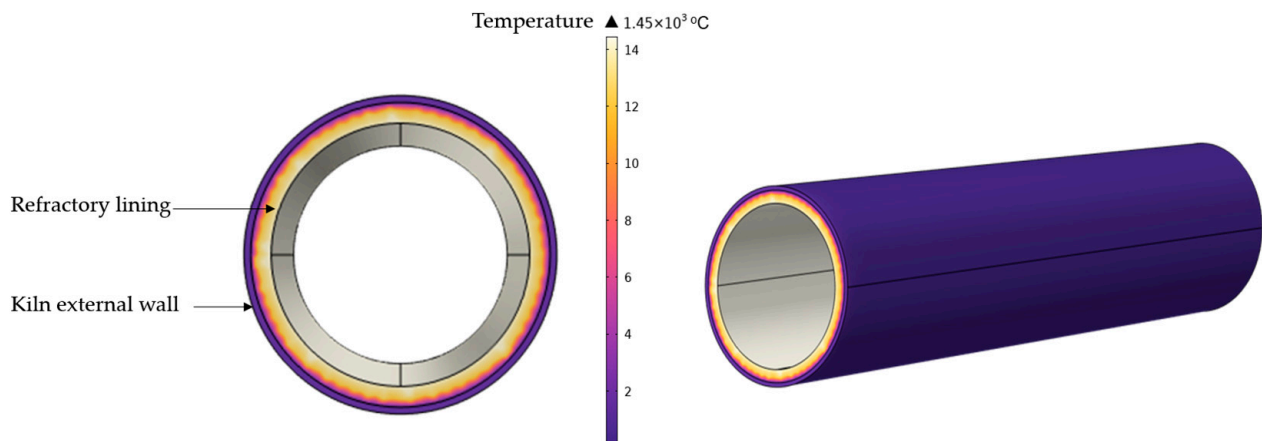


Figure 5. Simulated heat distribution in the refractory and kiln wall.

ii. *Simulation of heat profiles for the kiln axis*

Figure 6 shows the temperature profiles of clinker and fuel gas within the kiln. The clinker temperature begins relatively low at roughly 800 °C and gradually rises, peaking at approximately 1450 °C at 20 m into the kiln. This peak temperature is required to complete the necessary chemical processes within the clinker, which are critical for making high-quality cement. Beyond this peak, the temperature of the clinker continues to fall, dropping to around 1200 °C by the time it reaches 50 m. The fuel gases, which begin at about 1200 °C, reach a peak of around 1600 °C, but this occurs slightly earlier in the process, near the 15 m level.

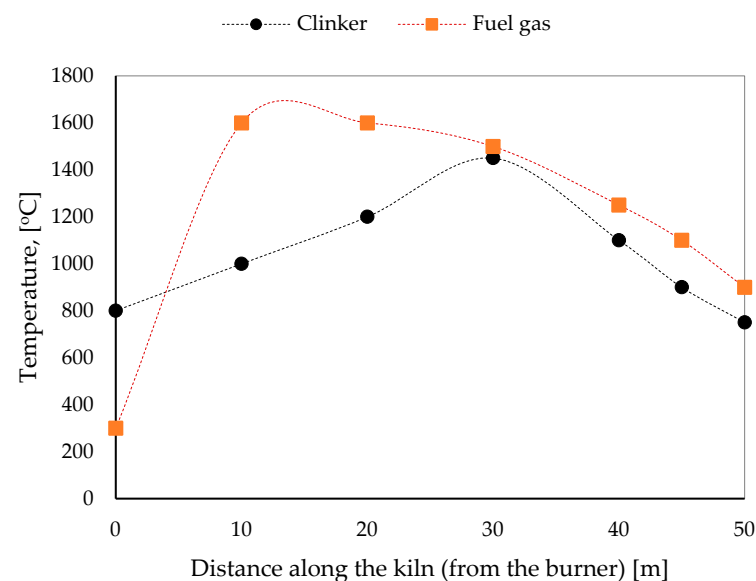


Figure 6. The temperature profile along the length of the kiln as obtained from the simulation.

The graph in Figure 7 shows the simulated heat distribution in the refractory and kiln wall at various clinker velocities. At a lower velocity of 0.2 m/s, the temperature rises rapidly, showing that the slower clinker velocity results in more heat absorption from the heating zone.

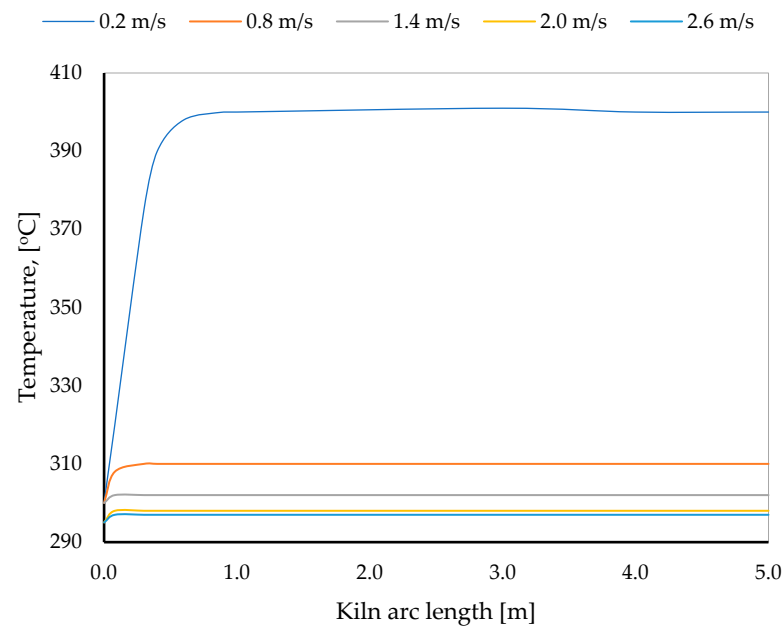


Figure 7. Simulated heat distribution in the refractory and kiln wall at various clinker velocities.

The extended exposure of clinker moving at a lower velocity of 0.2 m/s enables it to absorb heat more effectively and thoroughly. However, if the material moves too slowly, it could result in increased heat losses through the kiln walls due to the longer exposure times.

The graph in Figure 8 shows the link between the heat transfer coefficient (HTC) of the kiln refractory and wall and the increased velocity of the solid and gas phases. The graph indicates a linear increase in HTC as phase velocity increases. The heat transfer coefficient increases in proportion to the velocity of the solid and gas phases. This means that as the velocity of these phases increases, so does the rate of heat transfer between the kiln's refractory walls and the moving phases. The results also show that faster heating can result in more uniform temperature distribution within the kiln, lowering the time materials spend in the kiln and the overall energy required for processing.

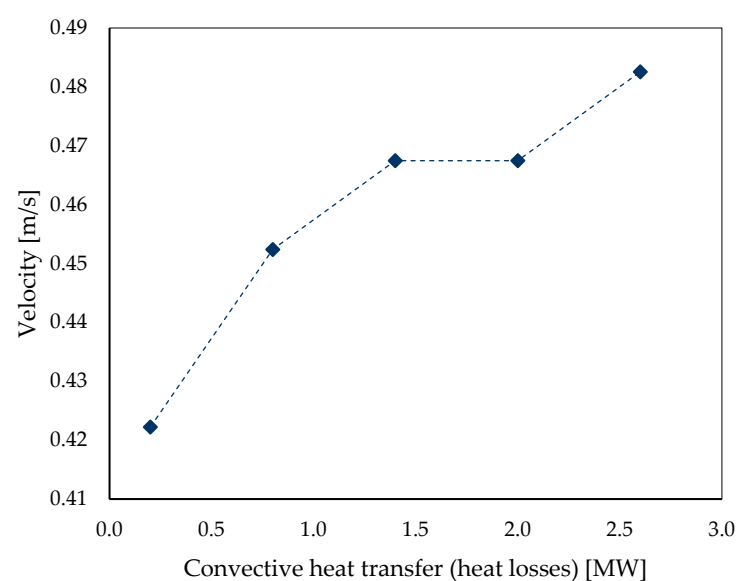


Figure 8. Simulated relationship between convective heat transfer (losses) and gas velocity within the kiln.

Figure 9 shows the relationship between convective heat transfer and gas velocity within the kiln, based on Equation (4). The convective heat transfer increases with the velocity of the gases. This trend indicates that higher gas velocities enhance the heat transfer coefficient, leading to more significant energy transfer but potentially greater losses as well, necessitating a careful balance for optimal kiln operation.

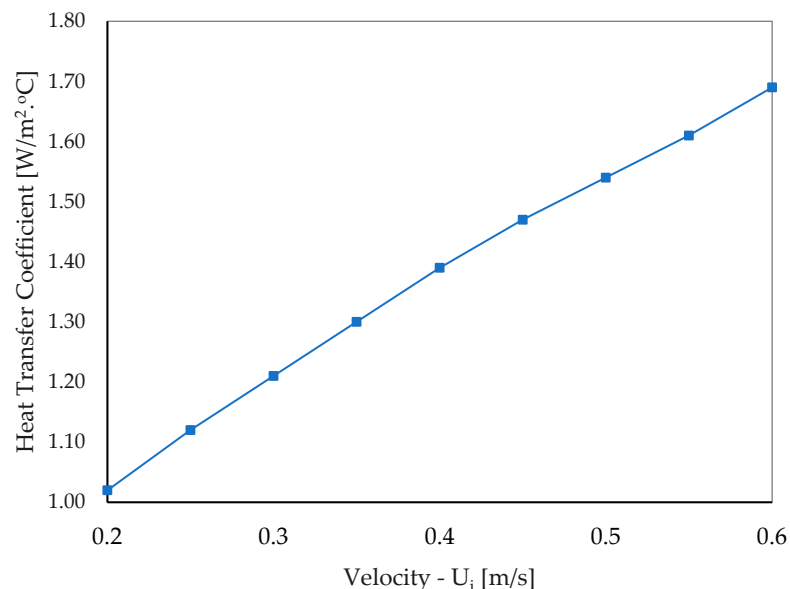


Figure 9. Heat transfer coefficient (HTC) of the kiln refractory at a varied velocity.

iii. Simulation of chemical reaction of raw mix.

Figure 10 shows the mass fraction of different mineral phases in clinker as a function of temperature, providing important information about thermal processing dynamics during clinker formation and the implications for heat losses. $\text{CaMgSi}_2\text{O}_6$ emerges at 450 °C and stabilises by 600 °C, demonstrating thermal stability in the absence of significant reactions at higher temperatures.

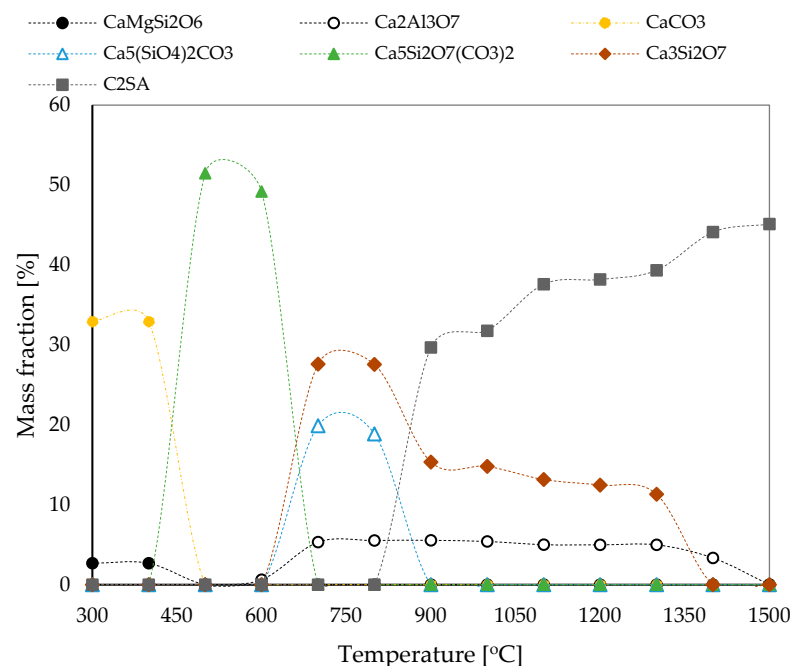


Figure 10. Mass fraction of mineral phases in clinker as a function of temperature.

$\text{Ca}_2\text{Al}_3\text{O}_7$ begins to develop at about 600 °C, peaking near 750 °C and subsequently decreasing, indicating that it is a transitional phase. Notably, $\text{Ca}_5\text{Si}_2\text{O}_7$ peaks at about 800–900 °C and then rapidly drops, indicating considerable CO_2 release and transition into other calcium silicate phases. Finally, C_2SA is formed at around 1200 °C and continues to increase until 1500 °C, highlighting its importance in the final clinker qualities due to its high-temperature stability.

4. Discussion

The results presented in Figures 5 and 6 show the heat distribution and transmission analysis inside a cement kiln, indicating the critical role that refractory lining plays in thermal energy management and operational effectiveness. The ability of the refractory material to insulate the kiln is demonstrated in Figure 5, which displays a reduction in temperature from the hot inner surfaces of the refractory to the colder outside surfaces of the kiln wall. This feature is critical because it prevents excessive heat from escaping into the environment, optimising energy use and reducing thermal inefficiency. The refractory lining acts not only as a barrier that absorbs and reduces high temperatures but also ensuring that the heat remains within the kiln to promote the chemical reactions required. The refractory linings with higher thermal resistance can greatly reduce heat losses to the environment, boosting the thermal efficiency of rotary kilns [40]. This was accomplished by combining curved refractory with additional fibre-insulating material, which can lower heat losses by 18–24% while increasing thermal unit efficiency. The selection of refractory material is critical to its performance and lifespan. Magnesia-spinelike refractories, for example, are used in cement kilns because of their strong heat resistance and chemical resistance to the calcined material [36]. Improving the thermal resistance of these linings can increase kiln efficiency by lowering heat losses.

The results obtained in Figure 6 show the clinker temperature peaking at about 1450 °C and the fuel gas temperature at around 1600 °C. These are the temperature ranges commonly used in rotary cement kiln operations [41–46], which show that the clinker reaches its peak sintering temperature near 1400–1450 °C, while the flame or gas stream may exceed 1500–1600 °C. This alignment indicates that the heat transfer processes and the overall thermal profile observed from the model results are consistent with the behaviour documented in similar rotary kiln studies.

The effect of gas velocity in cement kilns is critical for increasing heat transfer efficiency and reducing heat losses. Lower gas velocities, such as 0.2 m/s, have been proven to improve thermal efficiency by allowing the gas to spend more time in the initial heating zone, resulting in longer heat absorption and higher peak temperatures. The study by Njeng et al. [45] reveals that lower gas velocities (e.g., 0.2 m/s) result in higher peak temperatures at the beginning of the kiln due to extended heat absorption, which improves thermal efficiency and convective heat transfer [46]. Increasing cooling air mass flow by 1% improves exergy efficiencies by 0.06% and 0.04%, respectively. Conversely, increasing cooling gas temperature by 1% decreases these efficiencies by 0.09% and 0.07%. With lower velocities, the clinker's higher peak temperatures can stabilise as it moves through the kiln [47].

The chemical reactions and phase transformations involved in clinker formation, particularly concerning temperature and clinker velocity, play a crucial role in minimising heat losses and improving clinker quality. Slower clinker velocities enable extended heat interaction within the kiln, allowing for more thorough chemical transformations essential for forming stable, high-quality clinker phases such as $\text{CaMgSi}_2\text{O}_6$ and C_2SA . This controlled, slower processing not only leads to a more uniform clinker by reducing thermal gradients but also enhances energy efficiency by retaining heat within the system for longer,

which decreases the need for additional fuel. Consequently, effectively managing these parameters allows the cement manufacturing process to achieve higher thermal efficiency and produce superior clinker, resulting in more sustainable production practices. Optimising the velocity of clinker migration ensures that the heating and cooling phases within the kiln are better regulated, which leads to superior clinker quality. Clinker migration optimisation could potentially reduce energy consumption by 11–18% [48]. This control can also result in energy savings, since the process becomes more effective with improved heat management, using less fuel to maintain the required operational temperatures.

The heat transfer coefficient (HTC) in rotary kilns is a critical parameter influencing the efficiency of heat exchange between the kiln's refractory walls and the moving solid and gas phases. Understanding the relationship between HTC and the velocity of these phases can help optimise kiln operations, leading to more uniform temperature distribution, reduced processing time, and lower energy consumption. Studies [47–50] have shown that the HTC increases linearly with the velocity of the solid and gas phases. This relationship is crucial for enhancing heat transfer efficiency in rotary kilns. To reduce energy consumption and operational costs in the cement production process, efficient heat transmission in rotary kilns is essential [51]. By increasing heat transfer coefficients (HTCs), heat loss is decreased, and more energy is directed towards heating the clinker since there is less of a temperature differential between the kiln walls and the surrounding air. To guarantee clinker quality, however, adequate residence time for chemical reactions must be maintained.

Optimising kiln operations by adjusting heating and cooling rates can result in significant gains in thermal efficiency [52]. Such planned modifications ensure that not much time is spent at temperatures that are too high or too low for good reaction kinetics, hence reducing thermal inefficiencies. These operational changes, which reduce the time spent at sub-optimal temperatures, can reduce overall heat losses and improve the energy efficiency of the cement production process. This not only optimises resource utilisation but also fits with sustainability goals by lowering the environmental impact of energy consumption and CO₂ emissions in cement production.

The limitations of this study include simplification of assumptions, such as the interactions between fuel and particles, as well as changes in material properties under varying temperatures and conditions. The data on these variations were also limited. Despite these challenges, the modelling results remain robust and offer valuable clarity for improving energy consumption in cement production.

5. Conclusions

The dynamic simulations of heat transfer through the kiln's refractory lining and wall confirm the effectiveness of the refractory in minimising heat loss and maintaining thermal efficiency. The results demonstrate that heat transfer decreases progressively from the inner surface of the refractory to the kiln's outer wall, underscoring the importance of proper refractory design to control heat distribution and protect the kiln's structural integrity. The simulations also reveal that clinker and fuel gas temperatures follow distinct thermal profiles, with clinker temperatures peaking at approximately 1450 °C, which is essential for optimal chemical reactions in cement production.

The analysis of clinker velocities shows that lower velocities, such as 0.2 m/s, enable greater heat absorption, promoting effective thermal processing, but with the potential for increased heat losses due to extended exposure. Conversely, higher phase velocities enhance the heat transfer coefficient, resulting in improved heat transfer rates and more uniform temperature distribution within the kiln, reducing energy consumption and processing time.

The investigation into the mass fractions of mineral phases as a function of temperature also provides significant insights into clinker formation. The emergence and stabilisation of phases like $\text{CaMgSi}_2\text{O}_6$ and the transitional behaviour of $\text{Ca}_2\text{Al}_3\text{O}_7$ highlight critical thermal transformation points, while the development of C_2SA at high temperatures emphasises its contribution to clinker stability and quality.

These findings collectively offer valuable strategies for optimising kiln operation, enhancing energy efficiency, and improving clinker quality in cement manufacturing. By adjusting clinker velocities and phase velocities, producers can better control thermal dynamics, reduce heat loss, and achieve more sustainable production processes.

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