OPTIMIZATION OF HIGH SULFUR COAL
IN ROTARY KILN
OF CEMENT MANUFACTURING PLANT

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CERTIFICATE

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DEDICATION

This FYP Thesis is dedicated to individuals who believed in the potential of this group, especially, our beloved families, friends, and teachers who played a significant role in bringing us this far.

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Firstly, thanks to **Allah Almighty** for His countless blessings on us and for giving us the strength and ability to fulfill this project. The humblest and choicest salutations upon the **Holy Prophet Muhammad (Peace Be Upon Him)**, the mostperfect in this universe, who is forever a beacon of perfect guidance and knowledge for humanity. We are thankful to our **family andfriends**; we would not be here without their support and encouragement.

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Authors

ABSTRACT

Coal reserves in Pakistan are distinguished by their high sulfur content ranging from 5% to 7%. The combustion of fuel containing undesired compounds presents substantial challenges to the cement manufacturing industry, increasing the dependency on imported coal and depreciating those of origin. Furthermore, cement companies seek to find a way to ensure uninterrupted, cost-effective, and high-quality cement production that aligns with environmental standards in order to meet market demands.

The cement production process mainly focuses on the production of intermediate product clinker where large amounts of thermal energy are required to elevate raw material to sintering temperatures surpassing 1700 K. To meet this energy demand, a variety of fossil and alternative fuels are typically combusted through the primary burner located at the kiln's material outlet. However, the use of high-sulfur coal as fuel poses problems such as sulfur oxide emissions and spurrite ring depositions within the kiln leading to reduced kiln efficiency. To address these concerns, a solution was proposed by introducing an $Mg(OH)_2$ mixture as a reactive chemical additive in our process and modifying the equipment rotary kiln and coal mill accordingly. The success of this approach has been observed through increased clinker quantity, reduced power consumption, and minimized process-hold ups.

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CHAPTER 1

INTRODUCTION

1.1 The Need to Capture Sulfur Compounds

In general, the capture of sulfur compounds in solid carbonaceous is of paramount importance for several existing industries around the world. One of the few obvious reasons is that when involved in combustion reactions, SOx emissions are released which is a major contributor to air pollution and can have adverse effects on human health such as raising the risk of respiratory issues for workers and nearby communities. During a typical cement production process, sulfur dioxide is produced through the oxidation of sulfide or elemental sulfur found in the fuel during combustion. Additionally, in certain areas of the kiln system where there is enough oxygen and temperatures range between 300-600°C, sulfide or elemental sulfur present in raw materials can undergo 'roasting' or oxidation, leading to the formation of sulfur oxide emissions.

Therefore, capturing and removing sulfur compounds is justified, even if the sole rationale is focused on environmental control.

As if this environmental issue isn’t enough of a challenge, cement industries face another concern: the formation of sulfur, spurrite, and alkali ring deposition within the walls of rotary kilns in cement manufacturing plants. The presence of these formations detrimentally affects the operation by reducing the available surface area in the kiln for effective heat transfer. In critical scenarios, the accumulation of material in the pre-heater and the formation of rings within the kiln can result in operational disruptions and even complete shutdowns. At present, preventive measures against the build-up of deposits, crusts, and sulfur-based ring formation involve implementing cleaning procedures performed by personnel utilizing high-pressure equipment to dislodge and remove obstructions. However, this necessitates the temporary cessation of clinker manufacturing equipment to facilitate the cleaning process. Consequently, the production of clinker must be halted, leading to significant operational costs incurred during the downtime. Ultimately, the power usage required by the process increases as well.

Figure 2 SOx Emissions

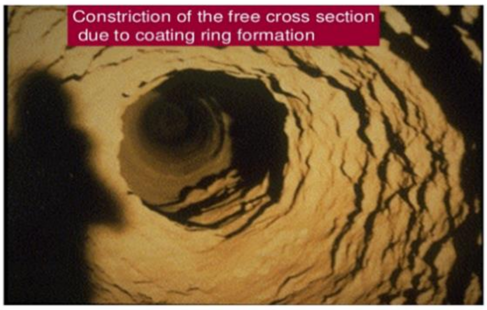


Figure 1 Ring formation

1.2 Phenomenon of Ring Depositions

The occurrence of build-up, crusts, and ring formation in rotary kilns arises from the direct interaction between sulfur, present in both fuels and raw materials, and alkalis, specifically sodium and potassium, inherent in the raw materials. This interaction leads to the formation of alkaline sulfates (e.g. Na_2SO_4 and K_2SO_4), which exhibit strong adhesion to the surfaces of the pre-heater and kiln. For example, sodium in fuel present as NaCl vaporizes quickly during the combustion of coal fuel, by which most of the sodium existing in vapor phase is converted to NaOH, where it exists as a gas at temperatures above 1388 °C. The SO_3 present in the fuel gases reacts with NaOH to form Na_2SO_4 as follows:

$$NaCl + H_2O \rightarrow NaOH + HCl$$
$$2\, NaOH + SO_3 \rightarrow Na_2SO_4 + H_2O$$

The formation of sulfur-induced rings arises when the molal sulfur to alkali ratio in the system exceeds 1.2, leading to a substantial presence of circulating free SO_3 within the kiln. In instances where the kiln operates under slightly reducing conditions, there is a heightened likelihood of volatile and lower melting sulfur salts forming, exacerbating the severity of the issue. These molten salts subsequently coat the moving clinker dust, compelling it to adhere to the kiln wall and manifest as rings. Similarly, the formation of carbonate or spurrite rings occurs either by the desorption of CO_2 into the recently generated free lime or by the re-carbonation of belite. The emergence of the third category of ring manifests in kilns characterized by elevated chlorine burdens when the molal sulfur-to-alkali ratio descends below 0.83. Under such circumstances, low-melting potassium salts serve as an adhesive medium for the clinker dust during its ascent within the kiln. Alkali rings are comparatively infrequent compared to other ring types due to the typical abundance of sulfur and carbonates relative to potassium.

It is worth noting that the chemical analysis of such rings may not reveal elevated sulfur concentrations, underscoring the fact that even a small quantity of free sulfur is adequate to initiate ring formation. The severity of this phenomenon escalates with the concentration of dust, an arduous waste byproduct, present in the kiln gas, with kilns possessing higher dust levels exhibiting a greater tendency to develop rings compared to cleaner kilns.

Moreover, the presence of compound vanadium in the fuel contributes to an accelerated formation rate of SO_3 and sulfated compounds intensifying the formation of build-ups and rings in both the kiln and pre-heater. The oxidation of sulfur dioxide to sulfur trioxide is facilitated by vanadium(V) oxide, wherein the vanadium(V) oxide undergoes reduction to vanadium (IV) oxide during this transformation.

$$SO_2 + V_2O_5 \rightarrow SO_3 + V_2O_4$$

In one of our major process units, the rotary kiln, the gas temperature spans from 450°C to 1550°C. During this range, the presence of vanadate in the fuel has the propensity to undergo solidification and accumulate within the walls of the rotary kiln. This is due to the characteristics of vanadate that exhibit a notable corrosion rate within the temperature range of 593°C to 816°C. At temperatures exceeding 816°C, different vanadate with a higher vanadium content form, leading to even higher corrosion rates.

Table 1 Melting points

Compound	Melting Point (°C)
V_2O_5	600-680
$Na_2O \cdot V_2O_5$	682
$Na_2O \cdot V_2O_4 \cdot 5V_2O_5$	535

Hence, an ideal approach to counteract any adverse impact on the cement clinker manufacturing process would involve employing a method that effectively addresses the presence of both sulfur and vanadium in the fuel simultaneously.

1.3 Methodology

To prevent the accumulation of deposits, formation of crusts or rings, as well as corrosion in the pre-heaters and/or kilns, an idea that involves the concurrent interaction of sulfur and vanadium present in solid carbonaceous fuels with an alkaline earth metal additive was enforced.

Firstly, it was done by preparing and formulating $Mg(OH)_2$ based additive solution composition such that it encompasses $Mg(OH)_2$ active content, a suspension stabilizer, and water miscible liquid. The percentage compositions are shown in the table below:

Table 2 Additive composition

Additive Composition	% Composition (w/w)
$Mg(OH)_2$ active content	40
Suspension stabiliser (Triethylamine) active content	3
Water miscible liquid	57

The method presented herein introduces a water-based fuel additive that effectively overcomes the undesirable reduction in kiln capacity caused by water injection in the combustion process. The alkali earth metal hydroxide and the stabilizer are combined in a water-miscible liquid medium to ensure their proper integration with the fuel. The presence of the liquid medium is essential because the alkali earth metal cannot be introduced in solid form due to the risk of it being drawn into the ID fan.

The solid carbonaceous mill operates at approximately 100°C, facilitating the evaporation of the liquid medium without the need for additional water. As a result, when the additive components reach the pre-heater and/or kiln, they are thoroughly dispersed within the fuel. It is important to note that the water content does not pose any harm to the system, as all the water is evaporated within the fuel mill.

It is then advanced inside the coal mill that plays a crucial role in the clinker production process by grinding large particles, some of which can reach sizes of 600 mm or more, into fine particles measuring between 75-90 microns. This size reduction enhances the combustion efficiency of the solid carbonaceous fuel, resulting in improved burning performance. However, introducing the additive in powder form directly into the fuel mill would lead to the immediate suction of particles by the ID fan into the electrostatic precipitators, preventing their proper mixing with the solid carbonaceous fuel. To address this, the fuel additive particles are mixed with water before the milling process, ensuring their dispersion on the solid carbonaceous fuel particles. Subsequently, these particles are ground together, optimizing the homogeneity of the mixture.

To ensure an effective dispersion of the alkali earth metal within the fuel and maximize its reactivity with both sulfur and vanadium, it is imperative to utilize an alkaline earth metal with a particle size below 20 microns. Larger particle sizes would not suffice as their reactivity would be insufficient. Note that the purpose of grinding is solely to facilitate the mixing of the fuel additive with the solid carbonaceous fuel, not to further reduce the particle size of the alkaline earth metal. This is because the solid carbonaceous mill achieves a 90% passing rate at 75 microns, making it unfeasible to achieve a particle size as small as 20 microns through grinding in the solid carbonaceous fuel mill alone. Consequently, the alkaline earth metal must already possess a particle size below 20 microns prior to its inclusion in step preferably falling within the range of 8 to 12 microns.

In the fuel mill, $Mg(OH)_2$ active part of the additive then reacts with the ring SO_3 and V_2O_5 to form stabler products as follows:

$$Mg(OH)_2 + SO_2 \rightarrow Mg(SO_4)_2 + H_2O$$
$$3\,Mg(OH)_2 + 5\,V_2O_5 \rightarrow Mg_3(VO_4)_2 + 6\,H_2O$$

1.4 Additive Dosage

The dosage of the one-component additive in the present solution is not contingent on the quantity of coal ash, but rather on the vanadium content present in the fuel which can be readily assessed using Flame Atomic Absorption Spectrometry.

The dosage is prepared according to the formula:

Additive dosage = V_2O_5 (ppm) χ Fuel Supply (ton/min) χ A

Given,

Fuel Supply = 66 tons/day

ρ additive = 1526.07 kg/m3

A = 0.957 / (0.5 x ρ additive)

Where,

A is a factor ranging from 1.0 to 4.0.

Assuming all trace vanadium (30 ppm of average Pakistani bituminous coal) of fuel forms V_2O_5 (1890 ppm) upon combustion of fuel:

$$4V + 5O_2 \rightarrow V_2O_5$$

Hence,

Additive Dosage = 1890 x 0.041 x 1.25 (kg/hr) = 4485.62 kg/day

The dosage formula for the additive is better determined based on the quantity of

V_2O_5 since the clinker production process occurs under standard oxidizing conditions, ensuring the conversion of all vanadium in the fuel to V_2O_5.

1.5 Basis of $Mg(OH)_2$ Additive Selection

Mg $(OH)_2$, as an alkali additive, offers distinct advantages over alternative alkali compounds such as MgO in specific applications. Herein, we outline the key reasons why Mg $(OH)_2$ is a preferred choice:

- Reactivity: The inherent alkaline nature of Mg $(OH)_2$ imparts it with remarkable reactivity. Its swift reaction with acidic compounds, such as sulfur, enables effective neutralization, thus averting their deleterious consequences. This reactivity underscores its efficacy in mitigating sulfur-related challenges encountered in industrial processes.
- Dispersion: Mg $(OH)_2$ exhibits exceptional dispersion characteristics within liquid media. Its facile integration with fuels or other substances engenders homogeneity throughout the system, ensuring uniform and comprehensive interactions. Consequently, the additive's effectiveness is maximized, yielding optimal outcomes.
- Stability: Mg $(OH)_2$ demonstrates commendable stability, particularly in aqueous environments. It remains suspended and retains its chemical properties over prolonged durations. This stability engenders consistent and predictable performance across diverse applications.
- Environmental Considerations: Mg $(OH)_2$ is regarded as an environmentally friendly choice in comparison to certain alternative alkali compounds. Its lower environmental impact and reduced likelihood of adverse effects during handling, usage, and disposal underscore its favorable environmental profile.
- Cost-effectiveness: Mg $(OH)_2$ often presents superior cost-effectiveness relative to other alkali compounds. This economic advantage positions it as a pragmatic option for industrial processes requiring alkali additives.

While the appropriateness of Mg $(OH)_2$ as an alkali additive may depend on specific process requirements, its reactivity, dispersion, stability, environmental considerations, and cost-effectiveness collectively establish it as a highly advantageous selection across numerous applications.

1.6 Role of TEA

To achieve particle dispersion in the liquid medium, as well as suspension stability and a shelf-life of at least 1 year, a suspension stabilizer Triethylamine (TEA), is introduced along with $Mg(OH)_2$ and water contents. This stabilizer plays a vital role in the formulation by ensuring proper particle dispersion in the medium and maintaining the stability of the final additive. Additionally, it facilitates an optimal interaction between the fuel and alkali earth metal during the grinding process, which is crucial for the reaction between the alkali earth metal particles and the sulfur/vanadium present in the fuel. In short, this formulation's effective particle dispersion and favorable fuel-metal interaction further enhance the formulation's performance.

1.7 Results

The methodology followed yielded highly favorable, productive outcomes and allowed us to go beyond reducing SOx emissions and kiln deposition.
Sulfur and spurrite ring formation was reduced as SO_3 and Vanadium in the hot meal underwent 1.2% and 61% decrease respectively. SOx and NOx emissions were also reduced as the ring-forming oxides were oxidized further to clinker-forming products before deposition.

Along with this, clinker formation was increased from 7500 tons per day to 8020.5 tons per day which is approximately a 7% increase, predicting an overall increase in production capacity.

The fuel efficiency has been observed to have increased as well. The fuel efficiency of coal was increased as the overall energy requirement of the plant was 5.86×10^9 (kcal/day) but after the implementation of our additive dosage system, it decreased to 5.44×10^9 (kcal/day).

CHAPTER 2

OPTIMIZATION TECHNIQUES

Notable techniques have emerged as promising strategies for addressing the challenges associated with high sulfur coal: the addition of $Mg(OH)_2$ in a water-miscible liquid with a suspension stabilizer in the coal mill and the standing coal biological pre-treatment with cultivated bacterial leaching through natural resources, employing acidithiobacillus bacteria. Another technique is through the optimization of operational parameters. While these techniques aim to optimize high sulfur coal, this study focuses on the former mainly due to its industrial feasibility as required by Bestway Cement Limited corporation.

2.1 Inherent Process

The utilization of standing coal biological pre-treatment with cultivated bacterial leaching, employing acidithiobacillus bacteria sourced from natural resources, represents a unique and effective approach to optimizing high-sulfur coal in cement manufacturing plants. This method takes advantage of the sulfur-oxidizing capabilities of acidithiobacillus bacteria, which help remove sulfur compounds from the coal, leading to notable improvements in the cement production process.

The optimization process begins with carefully cultivating and selecting acidithiobacillus strains that have strong sulfur-oxidizing abilities. These bacteria possess enzymes and metabolic pathways that efficiently oxidize sulfur compounds present in coal. Next, the selected acidithiobacillus strains are used in a leaching process applied to standing coal, which refers to coal that has not been previously extracted. During this process, the acidithiobacillus bacteria interact with the coal, initiating various biochemical reactions.

The leaching process involves the oxidation of sulfur compounds in high-sulfur coal, converting them into soluble sulfate ions whereas the acidithiobacillus bacteria utilizes sulfur oxidation as a metabolic process to derive energy, effectively reducing the sulfur content in the coal.

In addition, the interaction between acidithiobacillus bacteria and the mineral components of the coal leads to changes in the mineral composition. Sulfide minerals dissolve, and new secondary minerals with lower reactivity and reduced environmental impact are formed. Acidithiobacillus bacterial activity reaction followed by formation of secondary minerals is as shown:

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$$

$$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + CO_2 + H_2O$$

2.2 Optimization of Process Parameters

Dealing with high-sulfur coal in a rotary kiln of a cement plant requires careful optimization of process parameters to ensure efficient and environmentally friendly operation. Here are some key steps to consider:

Coal Selection: Choose coal with the lowest sulfur content possible. Coal suppliers should provide the coal analysis, including the sulfur content. Ideally, select coal with sulfur content below the maximum allowable limit for your cement plant.

Coal Blending: If low-sulfur coal is not readily available, consider blending high-sulfur coal with low-sulfur coal to reduce the overall sulfur content. The blend ratio will depend on the availability of low-sulfur coal and the desired sulfur content.

Preheating System: Optimize the preheating system to minimize the amount of sulfur released during the coal combustion process. Ensure the preheater cyclones are in good condition and functioning properly to achieve efficient coal combustion.

Kiln Operation: Adjust the kiln operating parameters to optimize the combustion process and minimize sulfur emissions. Some key factors to consider include:

a. Oxygen Levels: Monitor and control the oxygen levels in the kiln to ensure complete combustion of coal. Insufficient oxygen can lead to incomplete combustion and increased sulfur emissions.

b. Temperature Control: Maintain the appropriate temperature profile along the length of the kiln to ensure proper coal combustion. Higher temperatures can facilitate better sulfur capture.

c. Residence Time: Ensure an adequate residence time for the coal particles in the high-temperature zone of the kiln. Sufficient residence time allows for better sulfur oxidation and capture.

d. Kiln Speed: Optimize the kiln rotation speed to achieve the desired residence time and temperature profile. Adjusting the kiln speed can help control the combustion process and minimize sulfur emissions.

e. Kiln Fuel Distribution: Pay attention to the fuel distribution in the kiln. Uneven distribution can lead to localized high-temperature areas or insufficient combustion, affecting sulfur capture efficiency.

2.3 Process Selection Decision

The $Mg(OH)_2$ additive dosing system was preferred to the inherent process of removing sulfur from standing coal and the process of parameter optimization because the former process optimizes high sulfur coal in-situ. The high-sulfur coal is taken care of inside the existing process and no additional equipment or plant is set up for the production or application of additives.

It was also the requirement of the industry that no new plant or equipment be set up and the coal be optimized inside the existing process itself.

In previous studies, various methods have been proposed to control sulfur levels in different combustion systems by incorporating additives, particularly those containing magnesium oxide. However, these methods have been primarily applied to systems other than cement production and differ significantly from the solution presented here.

One of the earlier techniques describes an automated system for adding a magnesium oxide-based additive to the cement production process. The purpose of this system is to eliminate or minimize the formation of scales and rings in rotary kilns and boilers. The disclosed solution focuses mainly on the automated storage and application of additives, controlled by software. However, it lacks information regarding the specific formulation of the additive, recommended dosage amounts, measurement of the method's effectiveness in controlling build-up, crusts, and ring formations, among other aspects. The primary emphasis is on describing the components of the automated system, its features, and the benefits associated with controlling the addition of additives. The document does not provide any insights into the impact of magnesium oxide on the sulfur dioxide cycle or its effects on the clinker manufacturing process.

Another method is disclosed to address slag formation, which can contribute to ring formation, during the coal calcination process. This technique involves using a two-component additive: the first component is chosen from a range of magnesium-containing components, while the second component is selected from aluminum or copper acetates or nitrates, aluminum oxide or hydroxide, and ammonium phosphate. These ingredients can be directly added into the furnace or boiler or mixed with the coal before it is conveyed into the combustion chamber. The dosage of the additive depends on the coal ash content, so prior knowledge of this parameter is necessary.

In another patent, a process is described where magnesium carbonate ore is calcined with coal to capture toxic metals and reduce the formation of sulfuric acid during coal combustion. Unlike previous methods, the ore is added to the coal before combustion, and the resulting blend of magnesite and coal is pulverized and fired, producing very fine particles with a significant particle surface area. However, implementing this solution in practical applications requires access to a source of magnesium carbonate ore. One disadvantage is that it may be challenging to allocate space for the magnesium ore near the solid fuel in some plants, which limits its applicability.

A more recent method creates a mechanism to increase the boiler's efficiency by lowering SO3 by the injection of magnesium oxide. Through measurements of SO3 concentration at various locations throughout the system, monitoring the boiler's performance and the characteristics of the generated steam, a method is proposed to determine the dose and the best zone to include the magnesium oxide. The importance of vanadium (found in coal) as a catalyst for the conversion of SO2 to SO3 is emphasized, as well as the corrosion issues brought on by said vanadium. The rate of feeding magnesium oxide into the fuel/combustor, the rate of feeding magnesium oxide into the mid- and low-temperature regions, and the overall amount of magnesium oxide to be fed all rely on the process. This strategy is highly challenging for the industry to implement because performing experimentation each time one wishes to begin the clinker production process is almost impossible. Additionally, the Kiln Build-Up Removal patent concentrates on low-temperature systems that are not exposed to a gas recirculation mechanism, as in the clinker production process, or contact with other compounds, as in the raw meal clinker.

Approach To Reduce A water-dispersible, oil-soluble, water-in-oil emulsifying agent with an HLB value of between 4 and 10 and a water-soluble, oil-dispersible emulsifying agent with an HLB value between 20 and 40 are all disclosed in the Kiln Build-Up patent as an aqueous dispersion for liquid hydrocarbon fuels. For the slurry to remain stable for 4 months, a second emulsifying agent is required. Older patents only describe a process that uses magnesium hydroxide and requires two emulsifying agents to be stable and effective. Furthermore, only liquid hydrocarbon fuels are eligible for the dispersion stated in the application. Approach To Reduce The Kiln Build-Up patent describes a method of capturing sulphur released from burning carbonaceous fuels by providing an aqueous carbonaceous fuel composition slurry consisting of 60–80% by weight of carbonaceous fuel particles with an ash content of below about 5% by weight, 0.05–2.0% by weight of a non-ionic dispersant, and water. To this mixture, a sulphur capturing substance, selected from hydroxides, oxides, and carbonates of calcium, magnesium By doing this, it is ensured that the sulphur will remain bonded in the slurry as solid sulphide rather than oxidising during combustion. In order to prevent issues with slag formation, the method described by US4783197 requires a fuel with a maximum ash concentration of 5%. If the fuel is not pure coal, this means that the fuel must be purified before it can be utilised. The Method To Reduce Kiln Build-Up patent also specifies that the fuel must first undergo pre-treatment before being combined with the remaining elements of the disclosed slurry. The element vanadium is not mentioned.

A more recent technique has been developed to enhance boiler efficiency by reducing S03 emissions through the injection of magnesium oxide. The method proposes a process for determining the appropriate dosage and optimal injection zone for magnesium oxide by measuring S03 concentrations at various points in the system, monitoring boiler efficiency, and assessing the properties of the steam generated. The role of vanadium as a catalyst for the conversion of S02 to S03 is highlighted, along with the corrosion issues caused by vanadium. However, the exact in-fuel/in-combustor feed rate, mid and low-temperature feed rate, and total amount of magnesium oxide to be injected are left to experimentation, making it challenging to implement in industrial settings. Conducting experiments every time the clinker production process begins is impractical. Moreover, the Kiln Build-Up Removal patent focuses on low-temperature systems that lack gas recirculation mechanisms, as found in clinker production processes, or contact with other compounds, as in the case of raw meal clinker.

The Method to Reduce Kiln Build-Up patent describes an aqueous dispersion for liquid hydrocarbon fuels composed of magnesium hydroxide, water, a water-dispersible, oil-soluble emulsifying agent with an HLB value of 4-10, and a water-soluble, oil-dispersible emulsifying agent with an HLB of 20-40. The inclusion of the second emulsifying agent ensures stability for up to four months. However, this method is limited to liquid hydrocarbon fuels, and the use of magnesium hydroxide and the need for two emulsifying agents restrict its applicability. Additionally, the dispersion disclosed in the patent is specific to liquid hydrocarbon fuels.

The Method to Reduce Kiln Build-Up patent outlines a method for capturing sulfur released from burning carbonaceous fuels. It involves creating an aqueous carbonaceous fuel composition slurry consisting of 60-80% carbonaceous fuel particles with an ash content below 5% by weight, 0.05-2.0% of a non-ionic dispersant, and water. The slurry is then mixed with a sulfur-capturing substance, such as hydroxides, oxides, and carbonates of calcium, magnesium, and manganese, with particle sizes below 10 microns. This ensures that sulfur is bound in the slurry as solid sulfide before being converted into sulfur oxides during combustion. However, this method requires the fuel to have a maximum ash content of 5% to avoid slag formation issues, which means that non-coal fuels must undergo purification before use. Furthermore, the Method to Reduce Kiln Build-Up patent does not mention the presence of vanadium.

The prior art fails to reveal a method that is simultaneously easy to adopt by the industry and efficient to completely avoid corrosion, build-up, crusts, and ring formation in cement pre- heaters and kilns when sulfur and eventually vanadium is/are present in fuels.

Hence, the proposed method of additive dosing is much more efficient and suitable for optimizing high-sulfur coal as compared to the previous techniques.

CHAPTER 3

PROCESS DESCRIPTION

3.1 Process Flow Diagram

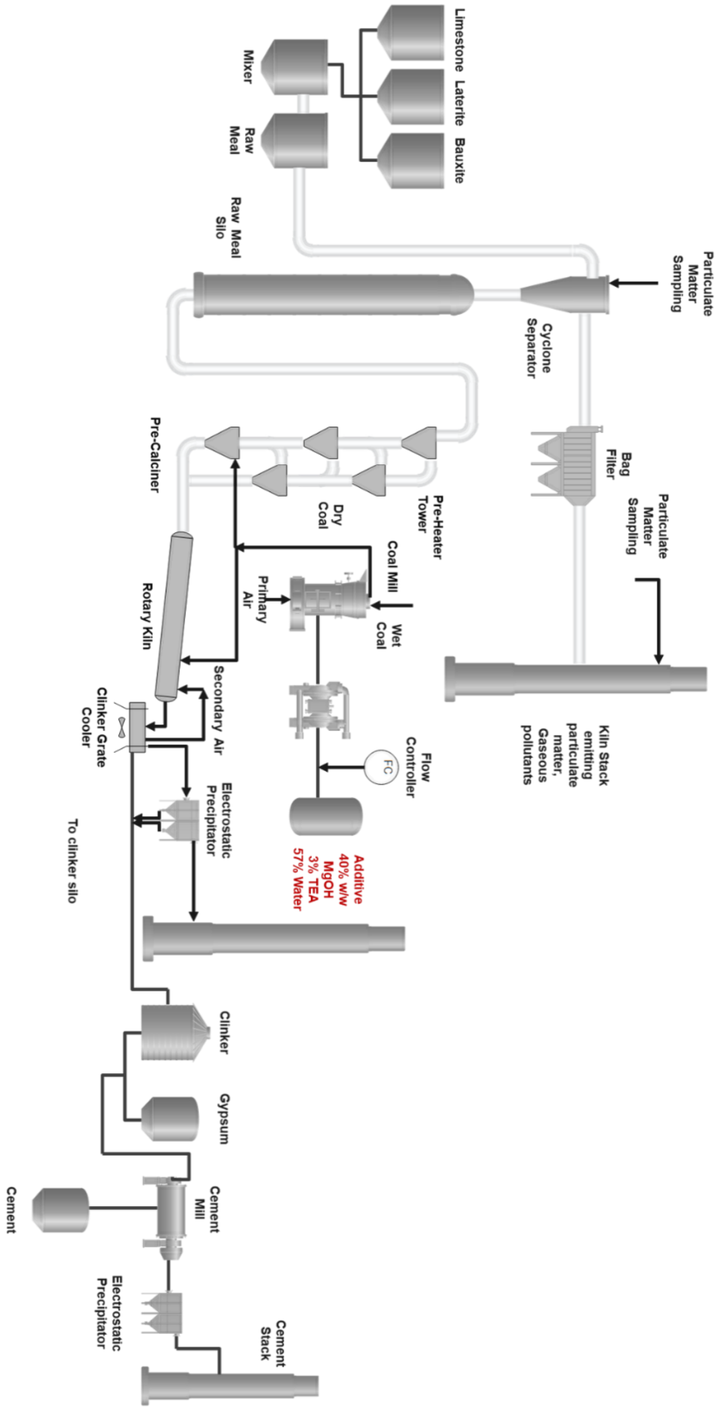


Figure 3 Process Flow Diagram

3.2 Process Description

Concrete is widely recognized as the most extensively utilized building material worldwide. Cement, the primary component of concrete, holds immense importance in the economic progress of modern society, finding application in various construction domains such as residential, commercial, and infrastructure projects. As a result, a thriving construction sector invariably leads to increased demand for cement production.

To meet market requirements, cement companies must ensure a continuous, cost-effective, and high-quality production process for cement.

The primary stage in cement production involves the thermal treatment of a mixture of materials, referred to as raw meal, comprising limestone, clay, iron ore, and other constituents. This mixture primarily consists of silicon, aluminum, iron, and calcium, along with minor quantities of sulfur, magnesium, sodium, potassium, and other substances. The preparation of raw meal involves initial steps of drying, crushing, and grinding. Subsequently, the raw meal is introduced into the pre-heater, where it undergoes gradual heating from approximately 200°C to 900°C to enable the conversion of CaCO3 in the raw meal to CaO and CO2. Following this, the calcined material, known as hot meal, enters the kiln and undergoes further heating from 900°C to 1500°C during the sintering phase. This critical step leads to the production of the primary component of cement, known as clinker. The clinker contains minerals such as tricalcium silicate (Ca3Si05, alite), dicalcium silicate (Ca2Si04, belite), tricalcium aluminate (Ca3AI206), and tetra-calcium aluminoferrite (4CaO· Al203Fe203), which impart distinctive properties to cement. The attainment of the aforementioned high temperatures necessitates significant energy input, typically derived from the combustion of fossil fuels. Coal and natural gas are the most commonly used fuels in cement production. However, their limited availability and high cost have compelled the cement industry to explore more economical alternatives and adapt their production processes accordingly.

Petcoke, a low-cost fuel, has emerged as the primary fuel employed by the cement industry today. Petcoke typically contains sulfur in the range of 4.5% to 8% on average. This fuel plays a crucial role in the combustion process, providing the necessary heat to sustain operational temperatures. However, when sulfur-containing fuels are burned, the sulfur is oxidized to form SO2, which adds to the sulfur dioxide originating from the raw materials. Consequently, the cumulative sulfur content becomes significant, leading to blockages, deposits, and ring formations in the pre-heater and kiln. This issue poses a serious challenge in the daily operations of cement plants, as production processes must be halted for equipment cleaning when these complications arise.

The occurrence of build-up, crusts, and ring formation arises when sulfur from both fuels and raw materials comes into contact with alkalis, such as sodium and potassium, present in the raw materials. This interaction results in the formation of alkaline sulfates (Na2SO4 and K2SO4), which exhibit strong adhesion to the surfaces of the pre-heater and kiln. Overlapping deposits of these substances accumulate, leading to the formation of build-up, crusts, or rings on the walls of the equipment. These formations pose challenges to operation by reducing the available surface area for heat transfer. In severe cases, blockages in the pre-heater and rings formed in the kiln can cause operational disruptions.

To prevent build-up, crusts, and sulfur-induced ring formation, cleaning procedures involving high-pressure equipment are conducted by personnel. However, these cleaning routines require the clinker manufacturing equipment to be stopped, resulting in production process interruptions and significant costs for operations.

If the fuel used contains vanadium, it can accelerate the formation rate of sulfur trioxide (SO3) and sulfated compounds, thereby increasing the occurrence of build-ups and rings in the kiln and pre-heater. Moreover, during the calcination and sintering phases, vanadium in the fuel can react with sodium in the raw meal to form various vanadates with different composition ratios. Vanadates with a composition of Na20-6 V205 exhibit high corrosion rates at temperatures ranging

from 593°C to 816°C. At temperatures above 816°C, other vanadates with a higher proportion of vanadium form, resulting in even higher corrosion rates.
$Na_2O\text{-}6V_2O_5 <\rightarrow Na_2O\text{-}V_2O_4\text{-}5V_2O_5 + 1/2\ O_2$ (eq. 1) Therefore, a method that simultaneously mitigates sulfur and vanadium present in the fuel should be ideal to prevent any negative effect in the cement clinker manufacturing line.

In previous studies, various methods have been proposed to manage sulfur content by introducing additives, primarily based on magnesium oxide, in different combustion systems. However, it should be noted that these approaches are typically implemented in systems other than cement production and differ substantially from the solution described in this context.

3.2.1 Additive process description

The additive process introduced in this method offers a new approach to address the simultaneous presence of sulfur and vanadium in solid carbonaceous fuels used during clinker production. By incorporating an alkaline earth metal additive into the fuel, the aim is to prevent the occurrence of build-up, crusts, ring formation, and corrosion in pre-heaters and kilns. Solid carbonaceous fuels encompass fuels obtained from the earth, such as coal, as well as by-products of oil refining, such as petcoke. The method involves the preparation, dosing, and utilization of a fuel additive comprising an alkaline earth metal that effectively captures both vanadium and sulfur present in these solid fuels. It is crucial for the fuel additive to exhibit sufficient reactivity to function optimally within the proposed method.

Another innovative aspect of this method pertains to the utilization of a water-based fuel additive. Injecting water into the combustion process is generally undesirable as it can reduce kiln capacity. Thus, the present method describes a water-based fuel additive that can be used without compromising kiln capacity, thanks to a unique usage method detailed below. Notably, unlike previous approaches, this solution requires only one component in the fuel additive to effectively eliminate ring formation in the kiln. Additionally, the dosage of this single-component additive is determined based on the vanadium content in the fuel rather than the amount of coal ash, which can be easily determined using techniques such as Flame Atomic Absorption Spectrometry or Inductively Coupled Plasma (ICP) Atomic Emission Spectrometry. An advantage of the present fuel additive is that the metal used in it can have a particle size distribution that is significantly higher than the range of 0.1-2 microns, simplifying its implementation in the industry. Furthermore, the fuel additive is suitable for various types of carbonaceous fuels with differing ash content, eliminating the need for pretreatment.

The current solution offers a unique and effective approach for capturing both sulfur and vanadium present in solid fuels used in clinker production. It involves combining sulfur and vanadium in the vapor phase with an added alkaline earth metal to prevent the formation of build-up, crusts, rings, or corrosion in pre-heaters and kilns. This method includes formulating a fuel additive composition based on alkaline earth metals and utilizing it when burning solid carbonaceous fuels.

Therefore, the objective of this solution is to present a method that simultaneously captures sulfur and vanadium from solid carbonaceous fuels used in the clinker production process. By adding an alkaline earth metal to the fuel, issues such as build-up, crusts, ring formation, and corrosion in pre-heaters and kilns can be avoided. The solid carbonaceous fuels typically contain sulfur in the range of 4.5% to 8% by weight and vanadium in the range of 500 ppm to 5000 ppm. The method involves the following steps:

a) Prepare a fuel additive composition, said fuel additive composition comprising:
- 20%-60% (w/w) of solid active content of an oxide or hydroxide of an alkaline earth metal;
- 0.5%-5% (w/w) of solid active content of a suspension stabilizer.
- 35%-79.5% (w/w) of a water-miscible liquid

b) Dosing the fuel additive prepared in step a) according to the formula:

Additive Dosage (ml/min)=V_205 (ppm) × Fuel Supply (ton/min) × A bl

Wherein V_20_5 (ppm) is the amount of V_20_5 in ppm that is formed considering that all the elemental vanadium present in the fuel react with oxygen to form V_20_5;

b2. A is a factor ranging from 1.0 to 4.0;

c) Add the fuel additive to the solid carbonaceous fuel;

d) Grind the fuel additive together with the solid carbonaceous fuel.

e) Feed the mixture fuel - fuel additive into the preheater and/or kiln, according to the needs of the clinker manufacturing process.

CHAPTER 4

MASS BALANCE

The law of conservation of mass, which forms the basis of the material balance, states that mass can neither be created nor destroyed and is always conserved in any process. Material balance, also known as mass balance, is a method of analyzing physical systems using the principle of mass conservation. Mass flows that would have been unknown or difficult to assess without this methodology, can be identified by accounting for material entering and leaving a system. Material balances are frequently used in chemical engineering calculations, especially for equipment design such as determining flows into and out of a gas absorption column and for evaluating reflux ratios and boil-up ratios. The general mass balance equation can be written as:

Accumulation within the system = (Mass into the system) – (Mass out of the system) + (Generation within the system) – (Consumption within the system)

(Eq. 4.1)

4.1 Methodology

For this project, we performed material balance to find out the values of major streams after having performed the parametric analysis. Initial calculations were performed by hand and then refined and copied to MS Excel. Material balance was done, initially, on the whole Cement plant and then on major equipment including:

1. Rotary Kiln
2. Coal Mill

4.2 Assumptions

1. Basis: 7500 tons/day of clinker production
2. All mass flow rates in kg/day.
3. Continuous, steady-state operation. Hence, accumulation = 0.
4. From the basis, we calculated the amount of feed required, and using that and the factors provided in handbooks we calculated the other parameters like air requirement and moisture calculation

4.3 Overall Material Balance

Table 3 Overall Material Balance

Mass In		Mass Out	
Parameter	**Value (kg/day)**	**Parameter**	**Value (kg/day)**
Kiln Feed	1.20×10^7	Clinker	7.542×10^6
Cooling Air	1.77×10^7	Cooler Vent Air	1.01×10^7
Fuel	6.60×10^4	Preheater Gases	1.44×10^7
Primary Air	3.67×10^5	ESP Return Dust	3.75×10^5
Conveying Air	3.97×10^5	Return Dust Loss	6.0×10^5
Kiln Feed Moisture	9.0×10^4		
Fuel Moisture	1.38×10^6		
Cooler Water Spray	4.20×10^5		
Coal Mill Additive	4.48×10^4		
Total Mass Input	3.30×10^7	Total Mass Output	3.30×10^7

4.4 Rotary Kiln

A rotary kiln is a critical component in the production process of cement plants. Inside the kiln, a series of carefully controlled reactions occur as the raw materials, including limestone, clay, and other additives, undergo a chemical transformation. The kiln operates at temperatures of around 1400-1500°C, allowing the raw materials to undergo a complex series of chemical and physical changes, resulting in the formation of clinker.

Table 4 Rotary Kiln Material Balance

Mass In (kg/day)		**Mass Out (kg/day)**	
Kiln feed	1.2×10^7	Hot Clinker	7.5×10^6
Primary air	3.68×10^6	Exhaust Gases	3.35×10^6
Conveying air	3.98×10^6	ESP Return Dust	3.75×10^6
Input moisture	9×10^5	Return Dust Loss	6×10^6
Total	2.06×10^7	Total	2.06×10^7

4.5 Coal Mill

A coal mill is a key component in the coal-fired power generation process. It is a pulverizing machine that grinds the coal into a fine powder, which is then used as fuel in the combustion process. Inside the coal mill, coal is fed into a rotating drum, where it is crushed and ground by rotating steel balls or rollers. The pulverized coal is then blown into the combustion chamber of the boiler, where it ignites and releases energy through combustion.

Table 5 Coal Mill Material Balance

Mass In (kg/day)		**Mass Out (kg)**	
Wet Coal (fuel)	66000	Dry Coal	64000
Additive	4485.62	Moisture removed	6482.62
Total	70485.62	Total	70485.62

Chapter 5

ENERGY BALANCE

The ability of a body to perform work is referred to as energy. Kinetic energy, potential energy, chemical energy, and internal energy are some of the different types of energy. These energies are interconvertible in a moving or dynamic system, making it difficult to distinguish all of them separately. In some circumstances, although, a certain type predominates.

The energy balance gives us a way to analyze a system and confirm that energy has indeed been conserved. In a chemical system, this balance is usually done based on heat flow or enthalpy, where, enthalpy is defined as the total heat content of a system. Other bases for energy balance in chemical engineering are internal energy and work. Energy balances are normally used to calculate the heattransfer between different surfaces or layers so that an appropriate design of the equipment can be made. They are also used to get an idea about the utilities required to run a plant.

5.1 General Energy Balance Equation

Energy cannot be created or destroyed, but it can be transformed from one form to another, and this postulate is known as the law of conservation of energy. In the language of thermodynamics, this postulate is represented by the general energy balance equation, which is as follows:

$$\Delta U + \Delta E_k + \Delta E_p = \boldsymbol{Q} - \mathrm{W}_{shaft} + \mathrm{W}_{\boldsymbol{f}}$$

(Eq 5.1)

$$here,\ \mathrm{W}_{shaft} = \mathrm{P}\Delta V\ \ \&\ \ H = U + \mathrm{P}\Delta V$$

The symbols used in the above equation are explained below:

Table 6 Symbols used in equations.

Symbol	**Meaning**
U	**Internal Energy**
H	**Enthalpy**
E_k	**Kinetic Energy**
E_p	**Potential Energy**
Q	**Heat**
W_{shaft}	**Shaft Work**
W_{flow}	**Flow Work**
P	**Pressure**
V	**Volume**

5.2 Assumptions & Simplifications

1. The Enthalpy of each stream was calculated using the following formula:

$$H_T = m \int_{To}^{T} CpdT$$

(Eq 5.2)

2. Kinetic energy & potential energy changes are negligible. Open system, so flow work is included and H is used instead of U. Applying the simplifications above, we arrive at the simplified energy balance equation:

$$\Delta H = \boldsymbol{Q} + \mathrm{W}$$

(Eq 5.3)

3. To calculate C_p of a mixed stream, containing more than one chemical species, the summability relation was used:

$$\mathbf{C_p(mixture) = x_A\, C_{p,A} + x_B\, C_{p,B} + x_C\, C_{p,C} + \dots} \qquad \text{(Eq 5.4)}$$

4. To calculate energy losses by convection and radiation, the following relations were used:

$$Qcon = \alpha con \times (Ts - Ta) \times As + \varepsilon \times \sigma \times ((Ts + 273.15)^4 - (Ta + 273.15)^4) \times As$$

$$Qrad = \varepsilon \times \sigma \times ((Ts + 273.15)^4 - (Ta + 273.15)^4) \times As$$

5.3 Methodology

As before, we performed energy balance to find out the enthalpies & heat duties of major equipment after having performed the parametric analysis. Initial calculations were performed by hand and then refined and copied to MS Excel. Heat capacity & mass enthalpy values were taken directly from the literature. Energy balance was done on major equipment including:

1. Rotary kiln
2. Coal Mill

5.4 Energy Balance on Rotary Kiln

We start by performing energy balance on Rotary Kiln.

Table 7 Rotary Kiln Energy Balance

Energy in (kcal/day)		**Energy out (kcal/day)**	
SH Primary Air	2.77×10^6	Preheater Losses	8.74×10^8
SH Conveying Air	3.00×10^6	Return Dust losses	3.50×10^7
SH kiln feed	1.92×10^8	Water Evap. losses	2.82×10^8
SH fuel dust	4.27×10^5	Heat of Formation	3.06×10^9
SH water	4.72×10^6	Kiln Radiation losses	1.05×10^8
SH kiln feed moisture	2.61×10^6	TAD Radiation losses	1.50×10^7
Heat from fuel	4.97×10^9	Cooler & Hood Radiation losses	3.75×10^7
Total Energy In	5.17×10^9	Preheater Radiation losses	2.10×10^8
		Clinker Dust Heat loss	3.50×10^8
		Clinker Heat loss	2.01×10^8
		Total Energy Out	5.17×10^9

5.5 Energy Balance on Coal Mill

Table 8 Coal Mill Energy Balance

Total feed to mill:	**66**	**TPH**		
Feed moisture:	14.5%(Balochistan Coal)	%		
Residual moisture:	1.5%	%		
False air:	18%	%		
	Mass(TPH)	Sp. Heat(kcal/kg/°C)	Temp.(°C)	Heat content (Kcal/h)(*1000)
INPUT				
Material	29.52	0.27	25	199.26
Water	6.48	1	25	162
Cooler Hot Air	121.487	0.24	280	8321.1
Recirculation Air	10	0.24	60	143.6
False Air	18.5319	0.24	60	132.7
Additive	0.1869	Using solid phase heat capacity data of MgOH	25	4.587
Grinding Heat	425 kW			347.7
Total Input:				9310.947

OUTPUT				
Material	29.52	0.29	70	599.256
Residual Water	0.422	1		46.4
Evaporated Water	6.058	1		5958.5
Air	150.019	0.24		2498.7
Additive:	0.1869	Using solid phase heat capacity data of MgOH		13.02
Radiation				92.5
Total Output				9308.376

CHAPTER 6

EQUIPMENT DESIGN

In this chapter, we look at the design of major equipment involved in the process of additive dosing of $Mg(OH)_2$ dosing. We'll only include the equipment that has been redesigned orhas been added to the existing process.

6.1 Rotary Kiln

Our process requires a specially designed kiln according to the parameters set by the use of our additive. For that purpose, a new kiln design has been proposed based on ratios and formulas from Cement Manufacturing Handbooks and from the data provided by the Bestway Cement Ltd. Industry liaison.

A rotary kiln is a large cylindrical vessel used in the manufacturing of cement. It is primarily used to calcine raw material into a process called clinker. The kiln is made up of a steel shell lined with refractory bricks, which can withstand high temperatures.

In the cement manufacturing process, raw materials such as limestone, clay, and other additives are crushed and ground into a fine powder. This powder, known as raw meal or raw mix, is then fed into the rotary kiln at one end.

Inside the kiln, the raw mix is heated at high temperatures (up to 1450 degrees Celsius or 2642 degrees Fahrenheit) and undergoes several chemical reactions. The most significant reaction is the formation of clinker, which is a nodular material with a diameter of a few millimeters.

The clinker formation occurs due to the combination of the raw materials' chemical compounds, primarily calcium carbonate (from limestone) and silica (from clay), along with other minor components. As the raw mix moves through the kiln, it is subjected to a series of temperature zones, each playing a crucial role in the clinker formation process.

The rotary kiln rotates slowly on its axis, allowing the material to gradually move from the inlet end to the discharge end. This rotational movement ensures an efficient heat transfer.

In addition to clinker formation, the rotary kiln also plays a role in other important processes in cement manufacturing. It helps in the decomposition of the raw materials, where carbonates are converted into oxides. It also facilitates the combustion of fuels, such as coal or petroleum coke, which provide the necessary heat for the kiln operation.

Once the clinker is formed inside the kiln, it is cooled and then ground into a fine powder along with a small amount of gypsum. This powder, known as cement, is the final product of the cement manufacturing process and is used in the construction industry for various applications.

Overall, the rotary kiln is a critical component in cement manufacturing, as it enables the transformation of raw materials into clinker through a complex series of chemical reactions, ultimately leading to the production of cement.

Table 9 Kiln Design & Sizing

Kiln Design & Sizing	
Kiln length	74 m
Kiln diameter	3.2 m
Kiln slope	4 degrees
Kiln speed	2.24 rpm
Design pressure	1.064 X 10^5 N/m^2
Operating pressure	1 atm
Operating temperature	1000 – 1400 degrees
Shell thickness	200 mm
Heat load per day	250000 kW
Clinker production output	8020 TPD
Kiln feed	12000 TPD
Fuel requirements (coal)	5000 TPD
Material of lining	Refractory brick lining
Material of construction	Mild steel
Cost of kiln	$ 2,000,000
Kiln operation	320 days/year
Annual maintenance cost	$ 2000
Annual operational cost	$ 30000

6.1.1 Kiln Shell Material

The shell of the proposed rotary kiln comprises of **rolled mild steel plate welded to form a cylinder**. Steel is used due to its strength and durability at high temperatures. The steel shell provides structural support and contains the materials being processed inside the kiln. However, the steel shell alone is not sufficient to withstand the extreme temperatures and chemical reactions that occur in the kiln. Therefore, the steel shell is lined with refractory bricks or castable refractory material.

6.1.2 Refractory Material

The proposed kiln is conventional in all aspects and therefore, makes use of a conventional **brick-lined interior** to contain and sustain the high temperatures inside it.

6.1.3 Kiln Diameter

The proposed kiln has a diameter of **3.2 meters**. This diameter has been calculated using degrees of slope and kiln diameter correlations found in the Cement Manufacturing Handbook.

The calculation of the diameter of a rotary kiln involves considering various factors such as the process requirements, material properties, and operational parameters. The primary considerations for calculating the diameter of a rotary kiln include the kiln capacity, retention time, and kiln speed. Here's a general approach to estimating the rotary kiln diameter.

6.1.4 Kiln Slope

It is generally 2° or 3.5 %. For calciner kiln up to 4% at a reduced speed. To promote the longitudinal travel of the solid, the proposed rotary kiln is mounted on a slope of 4%.

Therefore, the proposed kiln has a **slope of 4%.**

The slope of a rotary kiln refers to the inclination or angle at which the kiln is positioned. The kiln slope is an important parameter in the design and operation of a rotary kiln as it affects various aspects of the kiln's performance and material movement.

The slope of a rotary kiln is typically specified as the angle of inclination concerning the horizontal plane. It is commonly expressed in terms of a percentage or as a ratio of rise over run. For example, a kiln slope of 3% means that the kiln is inclined at a 3-degree angle from the horizontal.

6.1.5 Kiln Retention Time

Kiln retention time refers to the duration that a material or product spends inside a rotary kiln during the manufacturing or processing process. It is a critical parameter that directly impacts the quality and characteristics of the final product.

The retention time is determined by various factors, including the kiln's length, rotational speed, slope, and the desired degree of processing or transformation required for the material. It is typically expressed in minutes or hours and can vary depending on the specific application and industry.

The proposed Kiln Retention Time has been calculated using the following factors and formula.

Retention time (in minutes) = R = $\frac{(1.77)(\sqrt{Q})(L)(F)}{(S)(D)(n)}$

Where, Q = Angle of repose (usually 35 degrees)
L = Length of the kiln (m)
F = Multiplying factor (1)

S = Angle of slope

D = Kiln diameter

N = Number of revolutions per minute

Using **retention time 27 minutes**

L = $\frac{(R)(S)(D)(n)}{(1.77)(\sqrt{Q})(F)}$

L = $\frac{(27)(4)(3.2)(2.24)}{(1.77)(\sqrt{35})(1)}$

L= 74 m

6.1.6 Percentage Filling

The degree of filling in a rotary kiln refers to the extent to which the cross-sectional area of the kiln is occupied by the material being processed. It is an important parameter that affects the kiln's performance, heat transfer efficiency, and material residence time.

The degree of filling is typically expressed as a percentage, representing the ratio of the volume occupied by the material to the total cross-sectional volume of the kiln. For example, a degree of filling of 60% means that the material fills 60% of the available cross-sectional area of the kiln.

The degree of filling for the proposed kiln has been calculated as follows.

Percentage filling (%) = $\frac{(1.667)(T)(Q)(a)}{(Volume\ of\ kiln)(b)}$

T = retention time in minutes

Q = Capacity of clinker in the

a = Ratio of raw meal feed/ product = 1.5545

b = for clinker 1.2 t/m3

Percentage filling (%) = $\frac{(1.667)(27)(750)(1.5545)}{(3500.7)(1.2)}$

Percentage filling (%) = 12.49%

6.1.7 Kiln Revolutions Per Minute

The revolutions per minute (RPM) of a rotary kiln refer to the rotational speed at which the kiln rotates. The kiln speed is an essential parameter that influences various aspects of the kiln's operation and performance.

The kiln speed is typically determined based on factors such as the kiln's size, length, and the specific requirements of the process or material being processed. It is generally measured in revolutions per minute, representing the number of complete rotations the kiln makes within one minute.

The kiln rpm for the proposed kiln has been calculated as follows using formulas from the cement manufacturing handbook.

Using the equation of filling level:

% of filling level = $\frac{(3.2)(tonnes\ per\ day\ produced)}{(diameter^3)(kiln\ speed)(kiln\ slope)}$

Assuming a 12.5% filling level,

Kiln speed = $\frac{(3.2)(tonnes\ per\ day\ produced)}{(diameter^3)(\%\ filling)(kiln\ slope)}$

Kiln speed = $\frac{(3.2)(1150)}{(3.2^3)(12.5)(4)}$

Kiln speed = 2.24 rpm

6.1.8 Kiln Shell Thickness

The thickness of the shell in a rotary kiln refers to the thickness of the steel shell that encloses the kiln's internal processing chamber. The shell thickness is a critical design consideration as it ensures the structural integrity and longevity of the kiln.

Overall, the shell thickness in a rotary kiln is designed to ensure structural integrity, withstand mechanical and thermal stresses, and provide corrosion protection. The determination of the appropriate shell thickness is a critical aspect of kiln design to ensure safe and reliable operation.

Operating pressure = 1 atm
Operating temperature = 350 degrees
Diameter of the kiln = 3.2 meters
Design pressure at 5% above operating temperature
Design pressure = $\frac{(105)(1.013*10^5)}{100}$
Design pressure = 1.064×10^5 N/m^2

Therefore, the design stress for mild steel is 841 MPa.

Minimum thickness = $\frac{(design\ pressure)(diameter)}{2(design\ stress)-1.064*10^5}$

Thickness = $\frac{(1.064*10^5)(3.2)}{2(841*10^6)-1.064*10^5}$

Kiln shell thickness = 200mm

6.2 Coal Mill

In a cement manufacturing plant, a coal mill is used to pulverize coal for combustion in the cement kiln. The coal is fed into the mill through a central inlet pipe, where it falls under the gravity impact and is crushed by the rotating grinding table and rollers.

The primary function of the coal mill is to grind the coal to a desired fineness that is suitable for efficient combustion in the kiln. The grinding process in the coal mill reduces the coal particle size and increases its surface area, allowing for better combustion and heat transfer during the cement production process.

The coal mill typically operates in a closed circuit with a classifier, which separates the fine coal particles from the coarse ones. The fine coal particles are collected and sent to the kiln as fuel, while the coarse particles are returned to the mill for further grinding.

In addition to grinding coal, the coal mill may also dry the coal before it is introduced into the kiln. Drying the coal helps to improve the combustion efficiency by reducing the moisture content and ensuring a more stable flame in the kiln.

The coal mill is an integral part of the cement manufacturing process and plays a crucial role in the overall energy consumption and quality of the final cement product. It is designed to operate efficiently, ensuring the desired coal fineness and proper combustion characteristics to meet the specific requirements of the kiln system.

Safety precautions, such as proper ventilation and monitoring of carbon monoxide levels, are implemented to ensure the safe and reliable operation of the coal mill. Additionally, regular maintenance and inspection of the coal mill are conducted to ensure its optimal performance and minimize downtime.

It's worth noting that the use of coal as a fuel in cement manufacturing plants is gradually being phased out in many regions due to environmental concerns. Many cement plants are transitioning to alternative fuels, such as natural gas, petroleum coke, or biomass, to reduce carbon emissions and comply with environmental regulations.

The coal mill has been designed using the work index or bond method.

Table 10 Coal Mill Design & Sizing

Coal Mill Design & Sizing	
Table diameter	3.2 m
Roll diameter(standard)	8 inches
Roll length	25 inches
Table speed(rpm)	24.21
Number of master and slave rollers	2+2
Classifier diameter	4300 mm
Maximum working pressure(bar)	100
Minimum working pressure(bar)	55
Min. fan capacity(kW)	416
Max. fan capacity(kW)	1750
Mill total power(kW)	600

6.2.1 Bond Work Index Method

The coal mill has been designed using the Bond Work Index method using a work index of 13. Feed with 80% passing 1” and product 80% passing 0.001”.

The Bond Work Index (BWI) is a measure of the resistance of the material (in this case, coal) to grinding in a grinding mill. It is used to estimate the energy requirements for grinding and is commonly used in the sizing and selection of grinding equipment, including coal mills.

The Bond Work Index is determined through a standardized test known as the Bond Ball Mill Work Index Test. In this test, a defined amount of coal is ground in a laboratory-scale ball mill for a specified period. The resulting product size distribution is then used to calculate the Bond Work Index.

The Bond Work Index is calculated as follows:

$$BWI = 10 \, (\sqrt{(\frac{P80}{0.1})}$$

Where:

BWI is the Bond Work Index (kWh/t),

P80 is the 80% passing size of the product (in micrometers, μm), and
0.1 is a constant related to the test conditions.

The Bond Work Index indicates the energy required to grind the coal to a particular product size. It is commonly used in coal mill sizing and selection to estimate the power consumption and capacity requirements of the mill.

By using the Bond Work Index, engineers, and designers can determine the appropriate size and type of coal mill needed to achieve the desired grindability and product size distribution for a given coal feed. This information is crucial for the efficient operation and optimization of coal grinding processes in power plants, cement plants, and other industrial applications.

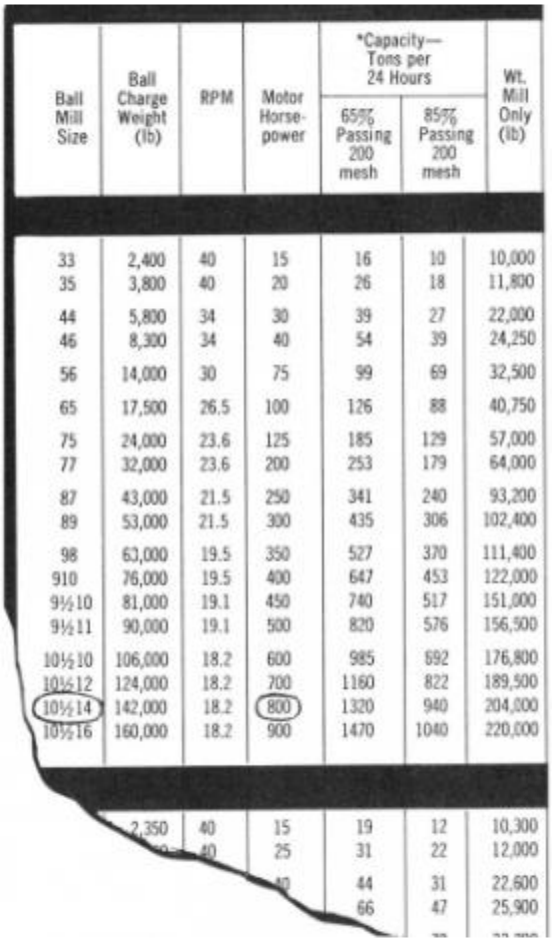
The following equation was used to calculate the Work Index.

$$W_i = W(\frac{\sqrt{Rr}}{\sqrt{Rr} - 1})(\sqrt{\frac{P}{100}})$$

Using Bond Work Index, the power requirement of the coal mill is calculated. Subsequently, using the power calculated, the coal mill is sized through formulas, tables, and charts available in the literature.

Operation stage	Vertical Mill Grinding
Hours per day	24
Tons per hour	36
Feed 80% size(mm)	25
Product 80% size(microns)	224
Reduction ratio(F/P)=	111
W_i/W=13.0/W	1.65
W(KWhr/ton)	7.861
HP or calculated power input=W×TPH×1.34	379.21

The following tables and charts were used to calculate Work Input and Coal Mill Size.



Ball Mill Size	Ball Charge Weight (lb)	RPM	Motor Horse-power	*Capacity—Tons per 24 Hours		Wt. Mill Only (lb)
				65% Passing 200 mesh	85% Passing 200 mesh	
33	2,400	40	15	16	10	10,000
35	3,800	40	20	26	18	11,800
44	5,800	34	30	39	27	22,000
46	8,300	34	40	54	39	24,250
56	14,000	30	75	99	69	32,500
65	17,500	26.5	100	126	88	40,750
75	24,000	23.6	125	185	129	57,000
77	32,000	23.6	200	253	179	64,000
87	43,000	21.5	250	341	240	93,200
89	53,000	21.5	300	435	306	102,400
98	63,000	19.5	350	527	370	111,400
910	76,000	19.5	400	647	453	122,000
9½10	81,000	19.1	450	740	517	151,000
9½11	90,000	19.1	500	820	576	156,500
10½10	106,000	18.2	600	985	692	176,800
10½12	124,000	18.2	700	1160	822	189,500
10½14	142,000	18.2	800	1320	940	204,000
10½16	160,000	18.2	900	1470	1040	220,000
	2,350	40	15	19	12	10,300
		40	25	31	22	12,000
			40	44	31	22,600
				66	47	25,900

Figure 4 Vertical Roller Mill Power

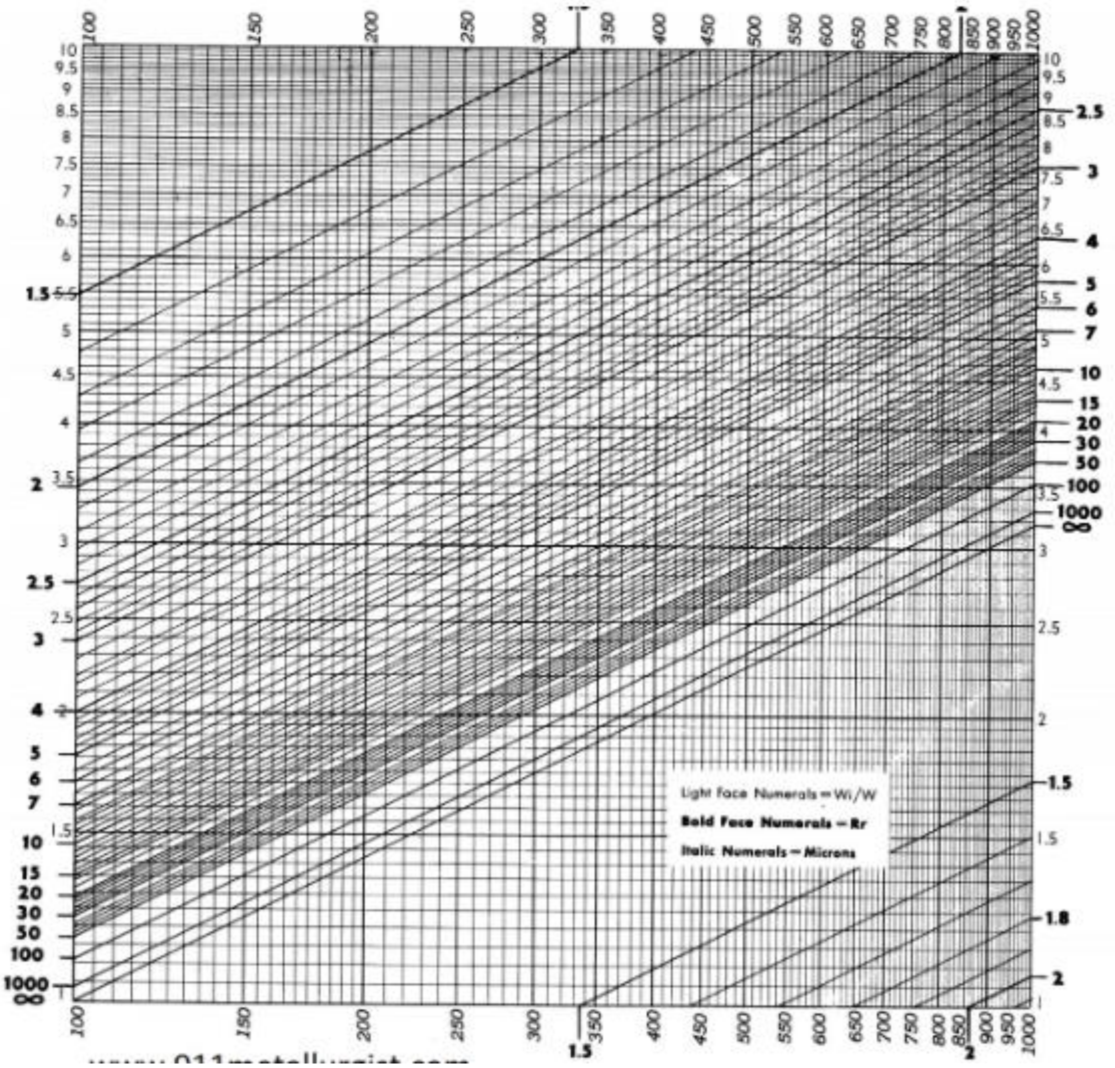


Figure 5 Work Index Chart

6.2.2 Coal Mill Table Diameter

The diameter of a coal mill table refers to the size of the grinding table or surface where the coal is pulverized and ground in the coal mill. The table diameter can vary depending on the specific design and model of the coal mill.

In coal mills, the grinding table is typically a rotating disc or a set of rotating discs on which the coal is ground. The coal is fed onto the table, and as the table rotates, the coal particles are crushed and ground by the grinding elements, such as rollers or grinding balls, which exert pressure on the coal.

The diameter of the coal mill table can vary depending on the mill size and capacity requirements. In large coal mills used in power plants, the table diameter can range from a few meters to over ten meters. For smaller coal mills used in cement plants, the table diameter is typically smaller, ranging from a few meters to around six meters.

The proposed coal mill has a **table diameter of 4.6 meters**.

6.2.3 Coal Mill Roll Diameter

The diameter of the coal mill table can vary depending on the mill size and capacity requirements. In large coal mills used in power plants, the table diameter can range from a few meters to over ten meters. For smaller coal mills used in cement plants, the table diameter is typically smaller, ranging from a few meters to around six meters.

The proposed coal mill has a **roll diameter of 8-inches** for the required application.

6.2.4 Coal Mill Roll Length

The length of the coal mill roll, commonly referred to as the grinding roll or grinding table, can vary depending on the specific design and size of the coal mill. Typically, the roll length in coal mills can range from a few meters to several meters. The length of the roll is an important parameter as it determines the grinding surface area available for coal grinding and the amount of coal that can be processed at a time. A longer roll length allows for a larger grinding surface area, which can increase the mill's capacity to grind coal efficiently. However, the specific length of the coal mill roll will depend on various factors, including the mill's design, capacity requirements, and the properties of the coal being processed.

A roll length of **25 inches** has been suggested for the current application.

6.2.5 Table Speed

The speed of the coal rolling mill table, also known as the grinding table or grinding disc, in a cement plant can vary depending on the specific design and requirements of the mill. Typically, the table speed in coal rolling mills for cement plants ranges from a few revolutions per minute (RPM) to several tens of RPM.

The table speed is an important parameter as it determines the grinding action and residence time of the coal on the grinding table. A higher table speed can result in a more aggressive grinding action, leading to finer coal particles and improved coal combustion efficiency. However, excessively high table speeds can also increase wear and tear on the grinding components, requiring more frequent maintenance and replacement.

The proposed coal mill has a table speed of **25 rpm.**

6.2.6 Maximum Working Pressure

The maximum working pressure of a coal roller mill, also known as a coal pulverizer or coal grinding mill, can vary depending on the specific design, size, and capacity of the mill. Typically, coal roller mills are designed to operate at relatively low pressures compared to other industrial equipment.

In general, the working pressure of a coal roller mill ranges from a few bars to several tens of bars. The pressure is generated by the grinding process and the airflow within the mill. Higher pressure can help to improve the grinding efficiency and coal fineness. However, the working pressure is limited by the structural integrity of the mill and the materials used in its construction.

The calculated maximum **working pressure is 100 bar**.

6.2.7 Minimum Working Pressure

Coal roller mills operate at atmospheric pressure or sometimes above atmospheric pressure. The grinding process in a coal roller mill relies on the rotation of the grinding elements (such as grinding rolls or grinding balls) and the movement of air or gas through the mill to facilitate coal grinding and drying.

Coal roller mills typically operate with a balanced airflow system, where the primary airflow provides the necessary transport of coal particles, and the secondary airflow aids in the drying process. The pressure requirements in a coal roller mill are mainly associated with the air or gas flow and are typically not specified as a minimum working pressure.

Therefore, the minimum **working pressure is 55 bar.**

6.2.8 Minimum & Maximum Fan Capacity

The minimum and maximum fan capacity of coal roller mills can vary depending on several factors, including the specific design, size, and capacity of the mill, as well as the coal properties and operational requirements. It's important to note that the fan capacity is determined based on the necessary airflow and pressure drop across the mill system.

The minimum fan capacity for the proposed coal mill is **416 kW**.

On the other hand, the maximum fan capacity of a coal roller mill is typically determined by the maximum airflow required for achieving the desired coal grinding rate and fineness. The maximum fan capacity is influenced by factors such as the mill size, coal properties, desired coal throughput, and grinding efficiency. It's essential to provide sufficient air or gas flow to maintain stable coal grinding and prevent overheating or blockages within the mill.

The maximum fan capacity for the proposed coal mill is **1750 kW**.

6.2.9 Coal Mill Grinding Capacity

The size of a coal mill in a cement plant can range from relatively compact units to larger structures, depending on factors such as the coal throughput capacity, desired coal fineness, and the layout and space availability within the plant. The size of the mill can also depend on the type of coal used and the specific requirements of the cement production process.

Coal mills in cement plants can have different configurations, such as vertical roller mills or ball mills, and the size can be influenced by the chosen mill type and design. Vertical roller mills are often more compact and have a smaller footprint compared to ball mills, but the specific size will depend on the specific model and design chosen for a particular plant.

The relevant mill has been designed and sized for **36 tons/hr coal grinding.**

6.3 Additive Dosing System

6.3.1 Additive Composition

The objective of this method is to simultaneously curb effect of both sulphur and vanadium from coal using an alkaline earth metal additive. Vanadium content is in the rang 500-5000 ppm.

Said fuel additive composition comprises:

- 20%-60% (w/w) of solid active content of an oxide or hydroxide of an alkaline earth metal.

- 0.5%-5% (w/w) of solid active content of a suspension stabilizer.

- 35%-79.% (w/w) of a water-miscible liquid

6.3.2 Additive Dosing Formula

The proposed $Mg(OH)_2$ additive is based on a specific formula that sets its basis on the V_2O_5 composition in the coal.

Additive dosage (kg/hr) = V_2O_5 (ppm) χ Fuel Supply (ton/min) χ A

Vanadium Pentoxide is found in all coals with a concentration range from extremely low to an alarming 10 g/kg.

6.3.3 Additive Flow Rate Calculation

Additive dosage (kg/hr) = V_2O_5 (ppm) χ Fuel Supply (ton/min) χ A

Additive Dosage = 1890 x 0.041 x 1.25 (kg/hr) = **4485.62 kg/day**

(The V_2O_5 has been taken as the average of the Vanadium Pentoxide present in Pakistani coals from various regions.)

6.3.4 General Steps for Additive Dosing

The following steps in order need to be executed to successfully administer the additive to the pulverized coal.

1. Prepare a fuel additive composition as described in the ratios.
2. Dosing of the fuel additive based on the formula.
3. Add fuel additives to solid carbonaceous fuel.
4. Grind additive together with solid carbonaceous fuel.
5. Feed the mixture of fuel and fuel additive to the preheater/kiln.

6.3.5 Additive Dosing Equipment

The additive dosing system has the following equipment.

Additive storage vessel:

The purpose of an additive storage vessel in a cement plant is to store and handle various additives that are used in the cement manufacturing process. Additives are materials that are added to the coal during or after the grinding stage to improve specific properties of the final cement product.

Here are some key purposes of an additive storage vessel:

Storage: The primary function of the additive storage vessel is to provide a dedicated space for storing different types of additives. These additives may include materials such as gypsum, limestone, fly ash, slag, or specific chemical compounds. The vessel ensures that the additives are kept in a controlled environment, protecting them from moisture, contamination, and degradation.

Controlled Dispensing: The storage vessel is equipped with mechanisms for the controlled dispensing of the additives. This can include features like screw conveyors, belt conveyors, rotary feeders, or pneumatic systems. These mechanisms allow for accurate and controlled dosing of the additives in the cement manufacturing process.

Inventory Management: The storage vessel helps in managing the inventory of additives by providing a centralized location for storing them. This allows for efficient inventory control, ensuring an adequate supply of additives is available for the cement production process. Regular monitoring and stock management help prevent production interruptions due to additive shortages.

Positive Displacement Pump:

A positive displacement pump plays a crucial role in additive dosing in a cement plant. It is commonly used to deliver additives accurately and precisely from the storage vessel to the desired location in the cement manufacturing process.

PD pumps are preferred over centrifugal pumps in various situations due to their unique advantages. PD pumps are particularly effective in handling viscous fluids, such as heavy oils and slurries, providing a steady flow regardless of viscosity. They also possess self-priming capabilities, enabling them to draw fluids from sources located above the pump or in intermittent flow situations. PD pumps can handle higher suction lift requirements, making them suitable for applications where fluid needs to be drawn from greater depths. Additionally, PD pumps deliver a constant flow rate, independent of changes in system pressure, which is advantageous in applications that require a consistent flow. Overall, the specialized features of PD pumps make them a preferred choice for applications that involve viscous fluids, challenging suction conditions, or the need for a steady and constant flow.

Pressure Relief Valves:

Pressure relief valves, also known as safety valves or pressure safety valves, are critical components used in various systems and equipment to protect against excessive pressure buildup.

Overall, pressure relief valves are essential safety devices that protect systems, equipment, and personnel from the dangers of excessive pressure. They provide an important layer of protection against overpressure situations, ensuring safe and reliable operation in various industries and applications.

Dispersion Nozzle:

Dispersion nozzles, also known as atomizing nozzles or spray nozzles, are commonly used to create a fine spray of additives in various industrial applications, including the dosing of additives in a cement plant.

A dispersion nozzle, also known as an atomizing or spray nozzle, is a device used to break down a liquid into a fine mist or spray. It works by introducing the liquid under pressure through a small orifice or series of orifices, creating high-velocity fluid streams that collide with each other and the surrounding air. This collision disrupts the liquid into small droplets, resulting in a dispersed spray. Dispersion nozzles offer several benefits, including efficient and uniform distribution of liquids, increased surface area for contact and reaction, improved mixing and absorption processes, enhanced cooling or humidification effects, and precise control over droplet size and spray pattern. These advantages make dispersion nozzles widely used in industries such as agriculture, chemical processing, pharmaceuticals, cooling systems, and various spray coating applications.

Dosing Process Controller:

A process controller for a dosing system is responsible for regulating and controlling the dosing process to achieve accurate and precise dosing of materials. It monitors the desired setpoint and adjusts the dosing parameters to maintain the desired dosage level.

A dosing process controller is a device used to accurately control and regulate the dosing of liquids or solids into a process. It operates by receiving input signals from various sensors or instruments that measure the desired parameters, such as flow rate, level, or concentration. Based on these inputs, the controller compares them to the setpoint or desired value and adjusts the dosing rate accordingly. The controller utilizes algorithms and control logic to calculate the appropriate dosing rate and sends control signals to the dosing system, such as pumps or feeders, to maintain the desired dosing level. The controller continuously monitors the process variables, adjusts as needed, and ensures precise and consistent dosing. It offers benefits such as improved accuracy, reduced human error, increased efficiency, and the ability to integrate with automation systems for seamless process control.

CHAPTER 7

PROCESS SIMULATION & PARAMETRIC ANALYSIS

For process simulation, Aspen Hysys simulation software was used:

7.1 Simulation main flowsheet

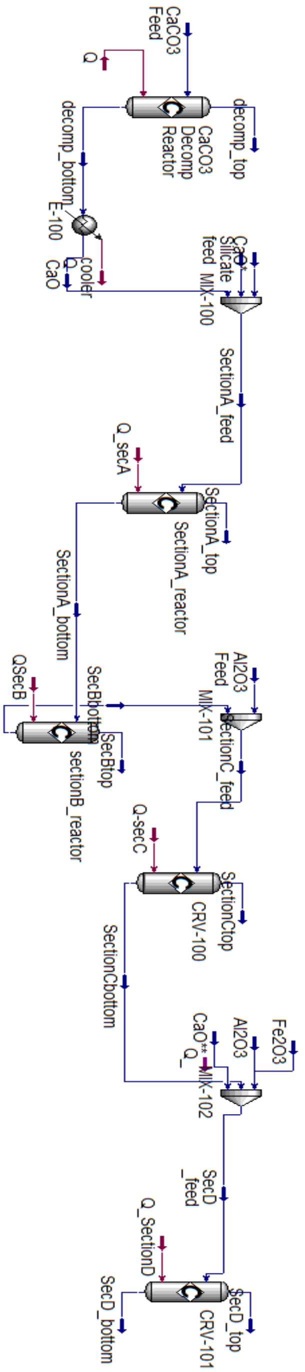


Figure 6 Main Flowsheet

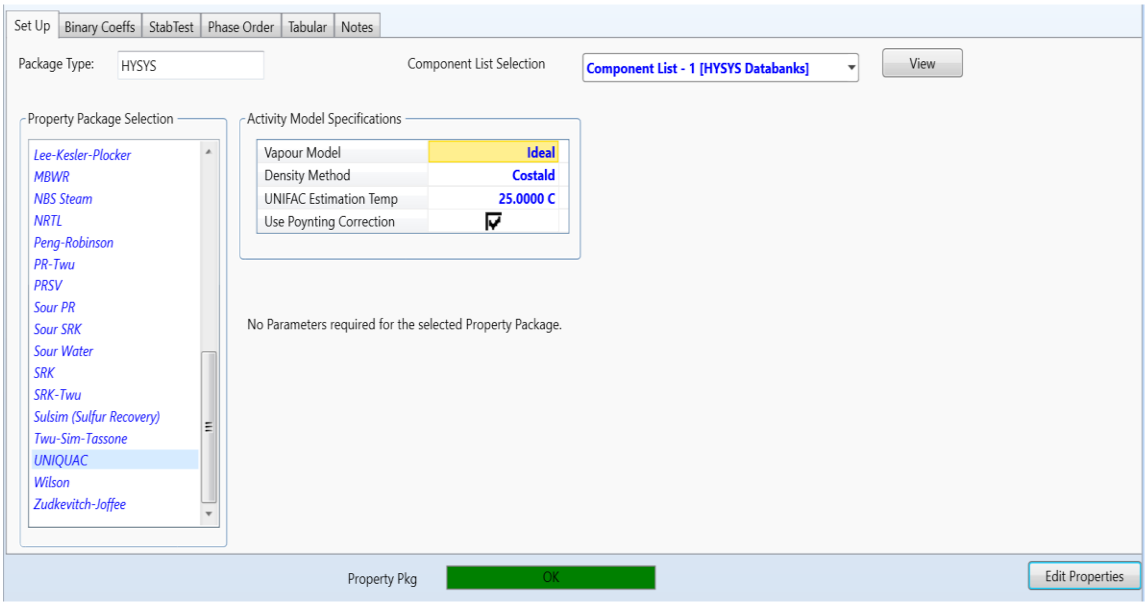
Due to the unavailability of models of compounds used in our process in the Aspen Hysys database.

(Raw meal (clinker-forming) and sintered product (clinker) compounds), the required compounds were entered into the simulation environment as hypothetical compounds with specified densities, and molecular weights and using in-built Hysys capability to estimate the remaining physical properties.

7.2 Fluid package

The fluid package is the set of equations that helps the program come up with relevant fluid properties at given states. Since a process is nothing but a change of states, the simulation needs underlying relationships to come up with values of properties about the system. The selection of the fluid package depends on the type of components involved.

Our choice of fluid package for simulation was UNIQUAC.



Package Type: HYSYS

Component List Selection: Component List - 1 [HYSYS Databanks]

Property Package Selection: UNIQUAC

Vapour Model	Ideal
Density Method	Costald
UNIFAC Estimation Temp	25.0000 C
Use Poynting Correction	☑

No Parameters required for the selected Property Package.

Property Pkg OK

Figure 7 Fluid Package

7.3 Kiln reactor

To simulate the rotary kiln, we have modeled it as a series of reactors, each of which simulates a clinkering reaction that corresponds to certain physical conditions found in the temperature zones that exist in a kiln. These zones are illustrated in the following figure:

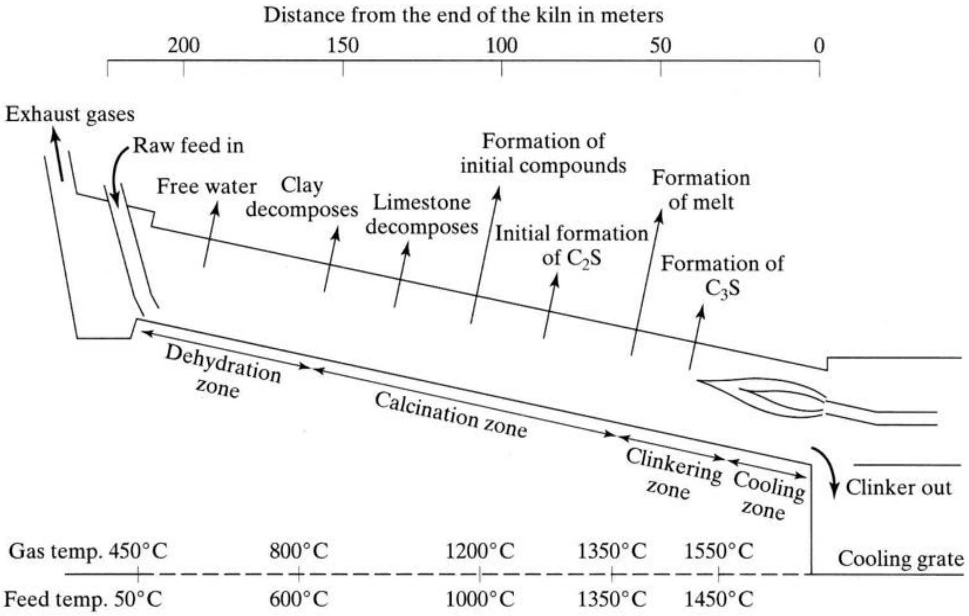
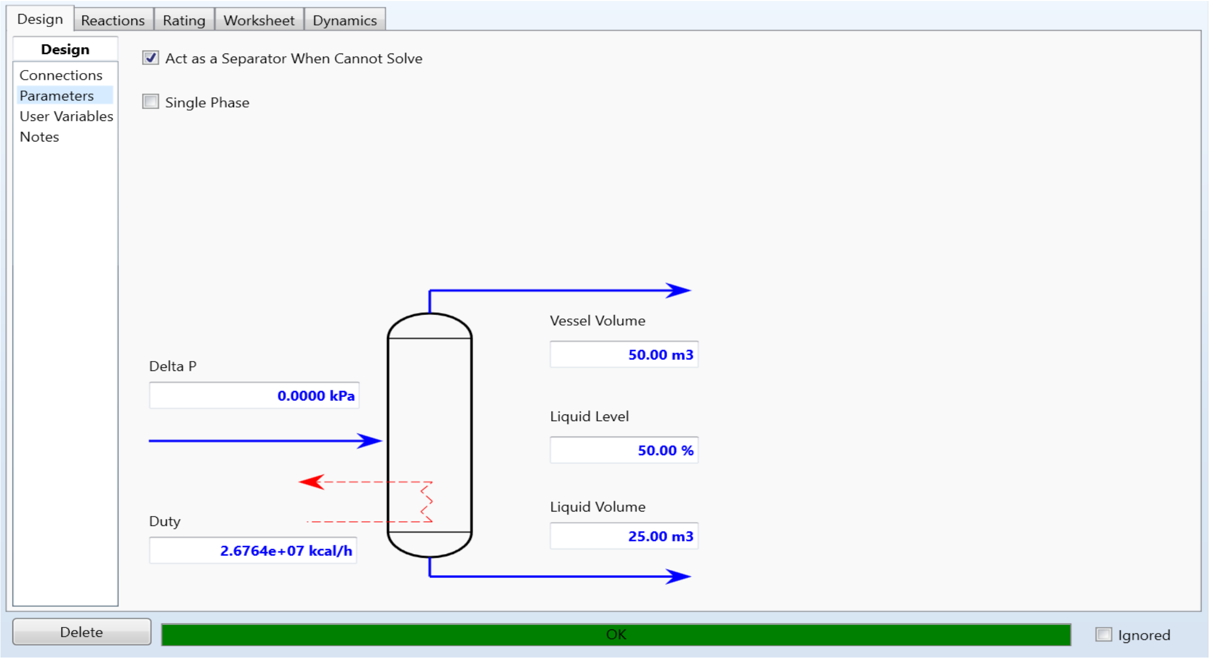


Figure 8 Kiln Temperature Zones

7.3.1 Reactor 1



☑ Act as a Separator When Cannot Solve

☐ Single Phase

Delta P: 0.0000 kPa

Duty: 2.6764e+07 kcal/h

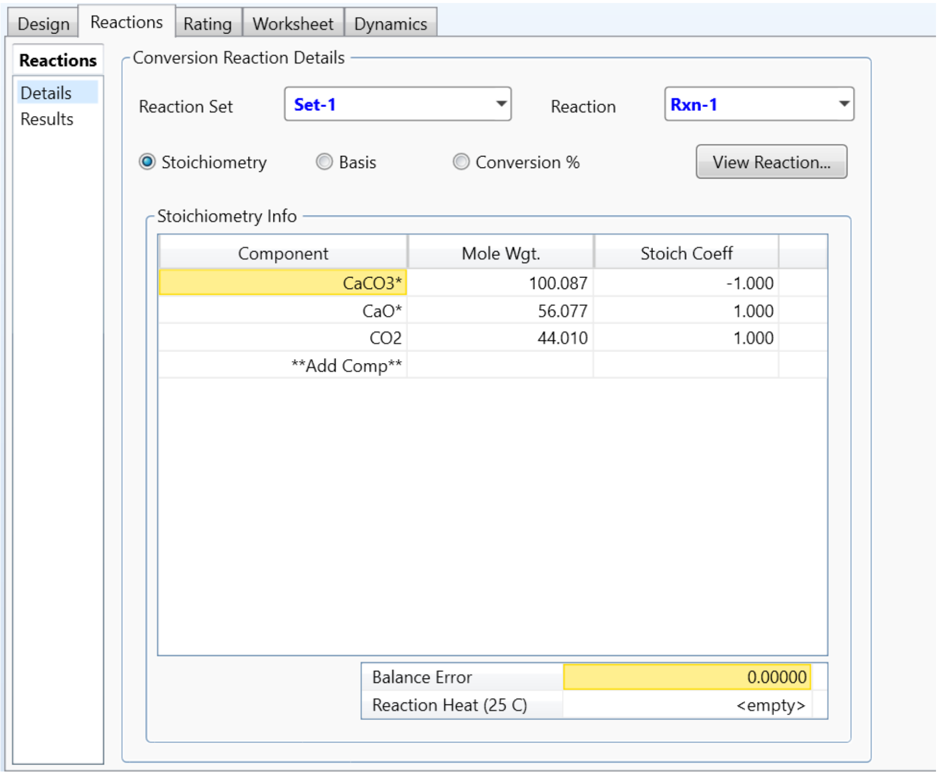
Vessel Volume: 50.00 m3

Liquid Level: 50.00 %

Liquid Volume: 25.00 m3

OK

☐ Ignored



Conversion Reaction Details

Reaction Set: Set-1

Reaction: Rxn-1

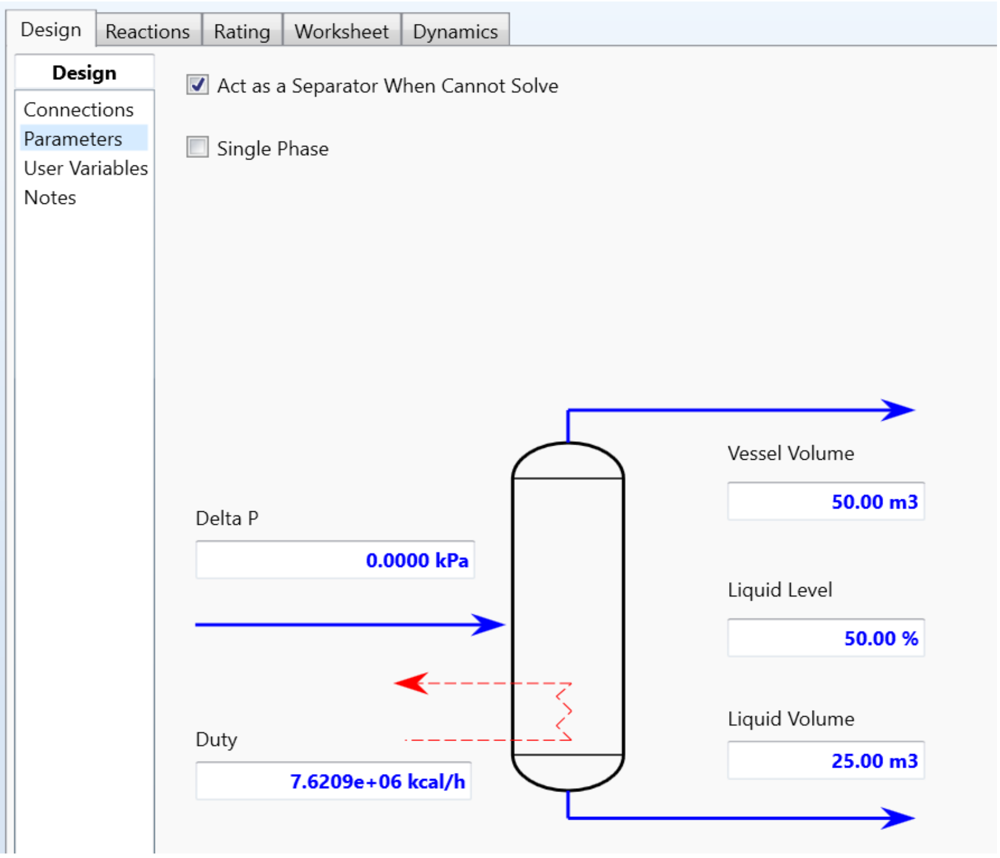
● Stoichiometry ○ Basis ○ Conversion %

Stoichiometry Info

Component	Mole Wgt.	Stoich Coeff
CaCO3*	100.087	-1.000
CaO*	56.077	1.000
CO2	44.010	1.000
Add Comp		

Balance Error	0.00000
Reaction Heat (25 C)	<empty>

7.3.2 Reactor 2



☑ Act as a Separator When Cannot Solve

☐ Single Phase

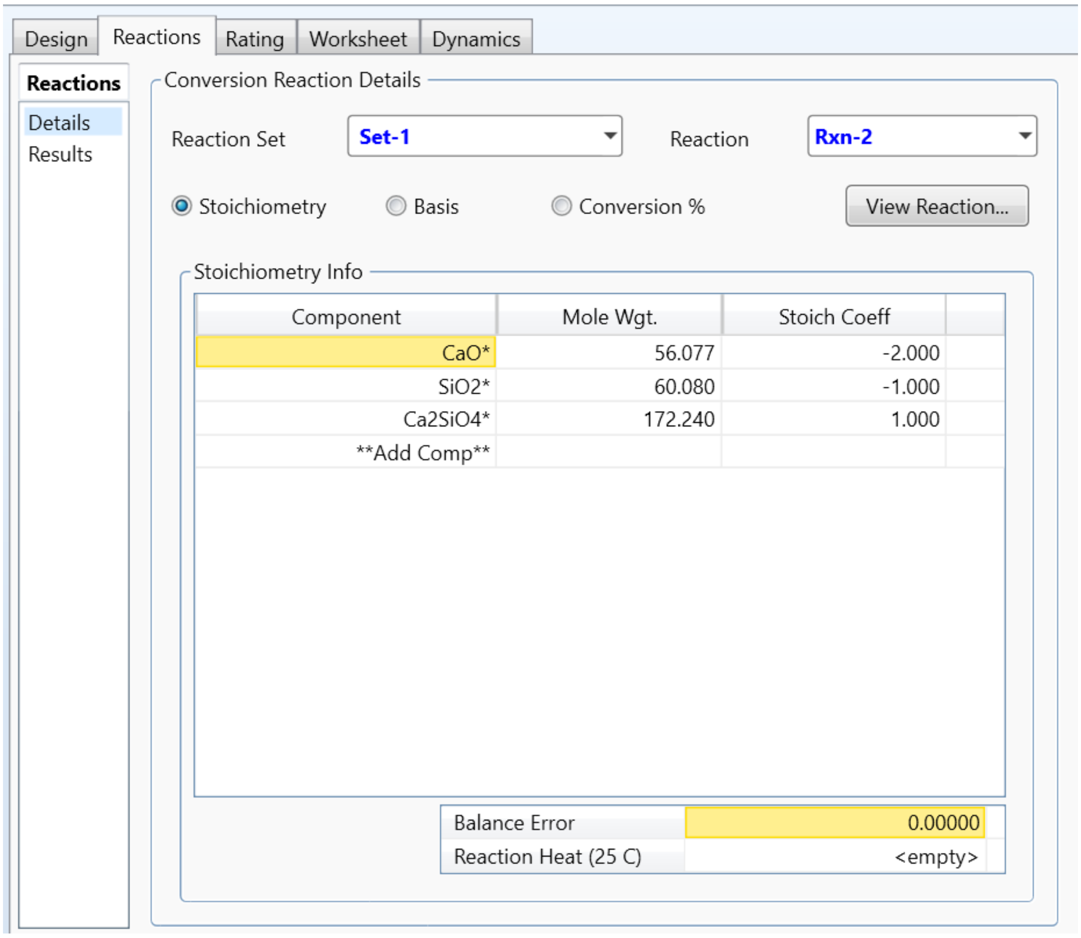
Delta P: 0.0000 kPa

Duty: 7.6209e+06 kcal/h

Vessel Volume: 50.00 m3

Liquid Level: 50.00 %

Liquid Volume: 25.00 m3



Conversion Reaction Details

Reaction Set: Set-1

Reaction: Rxn-2

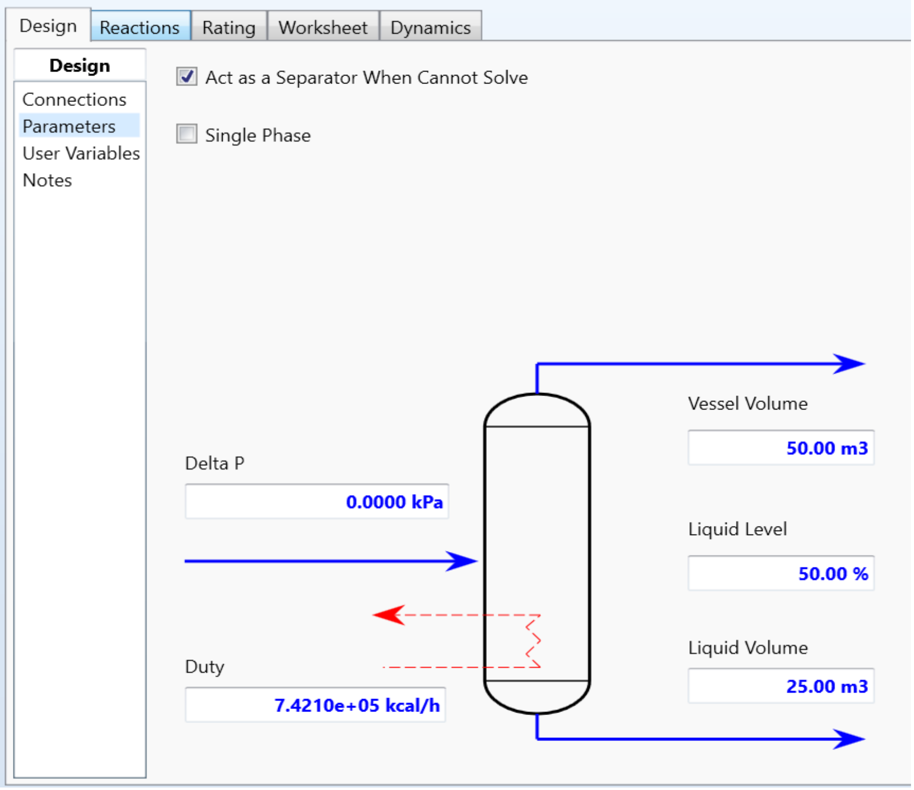
● Stoichiometry ○ Basis ○ Conversion %

Stoichiometry Info

Component	Mole Wgt.	Stoich Coeff
CaO*	56.077	-2.000
SiO2*	60.080	-1.000
Ca2SiO4*	172.240	1.000
Add Comp		

Balance Error	0.00000
Reaction Heat (25 C)	<empty>

7.3.3 Reactor 3



☑ Act as a Separator When Cannot Solve

☐ Single Phase

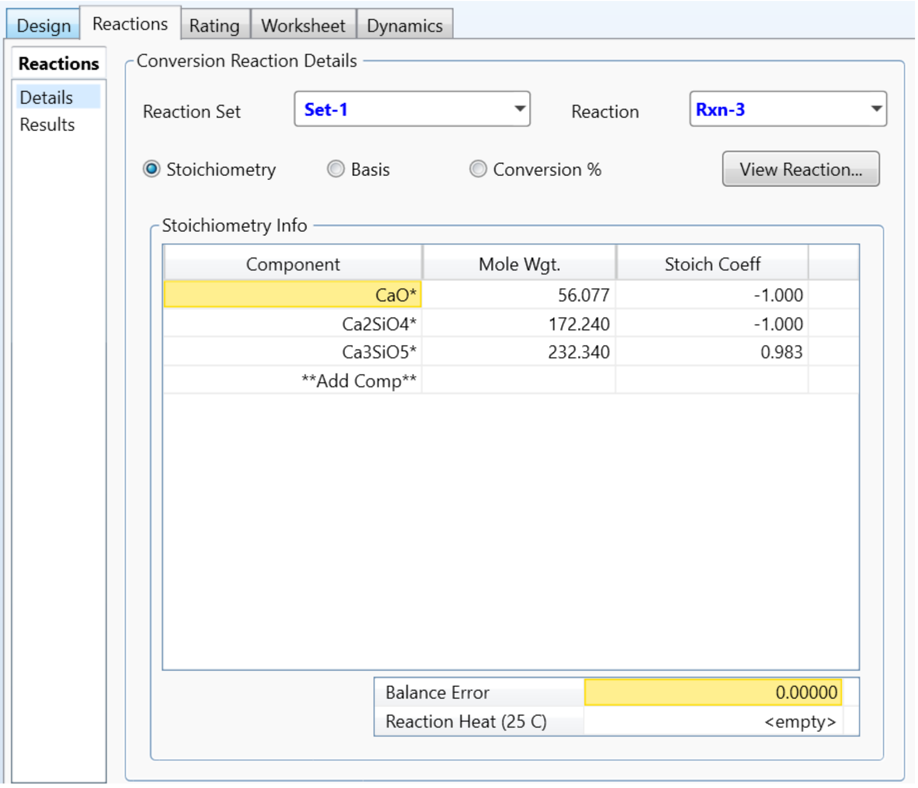
Delta P: 0.0000 kPa

Duty: 7.4210e+05 kcal/h

Vessel Volume: 50.00 m3

Liquid Level: 50.00 %

Liquid Volume: 25.00 m3



Conversion Reaction Details

Reaction Set: Set-1

Reaction: Rxn-3

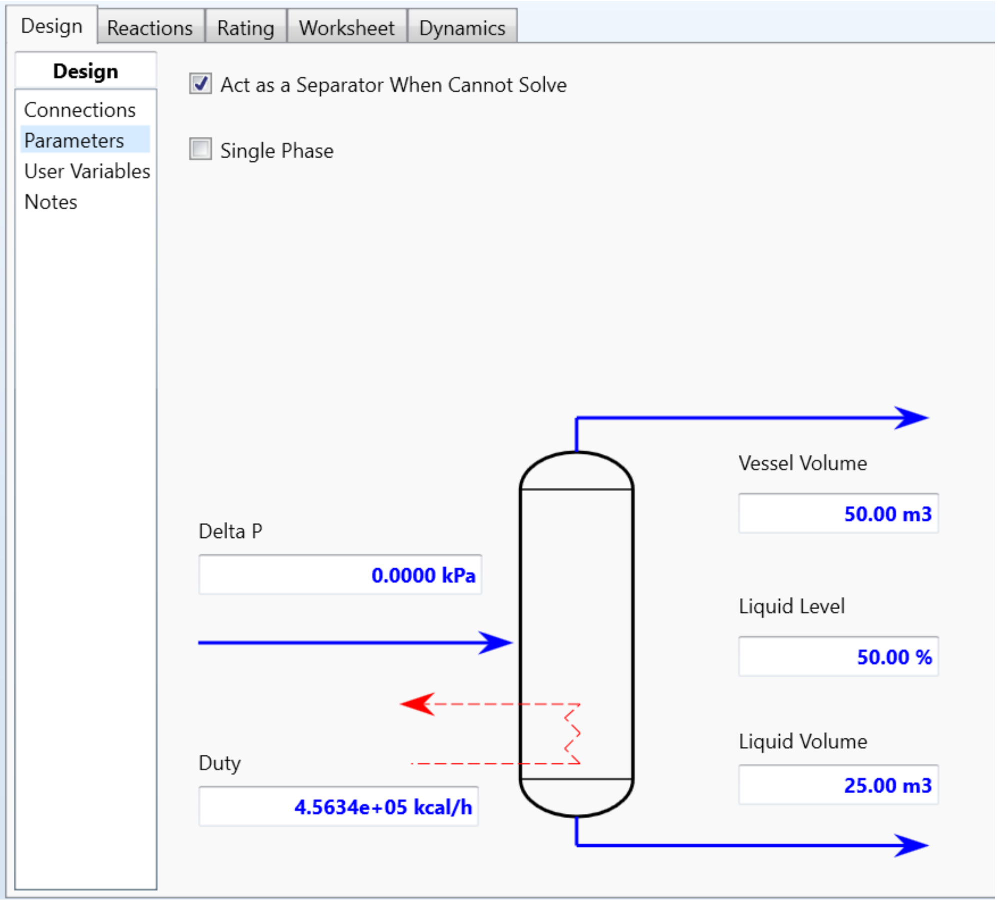
● Stoichiometry ○ Basis ○ Conversion %

Stoichiometry Info

Component	Mole Wgt.	Stoich Coeff
CaO*	56.077	-1.000
Ca2SiO4*	172.240	-1.000
Ca3SiO5*	232.340	0.983
Add Comp		

Balance Error	0.00000
Reaction Heat (25 C)	<empty>

7.3.4 Reactor 4



☑ Act as a Separator When Cannot Solve

☐ Single Phase

Delta P: 0.0000 kPa

Duty: 4.5634e+05 kcal/h

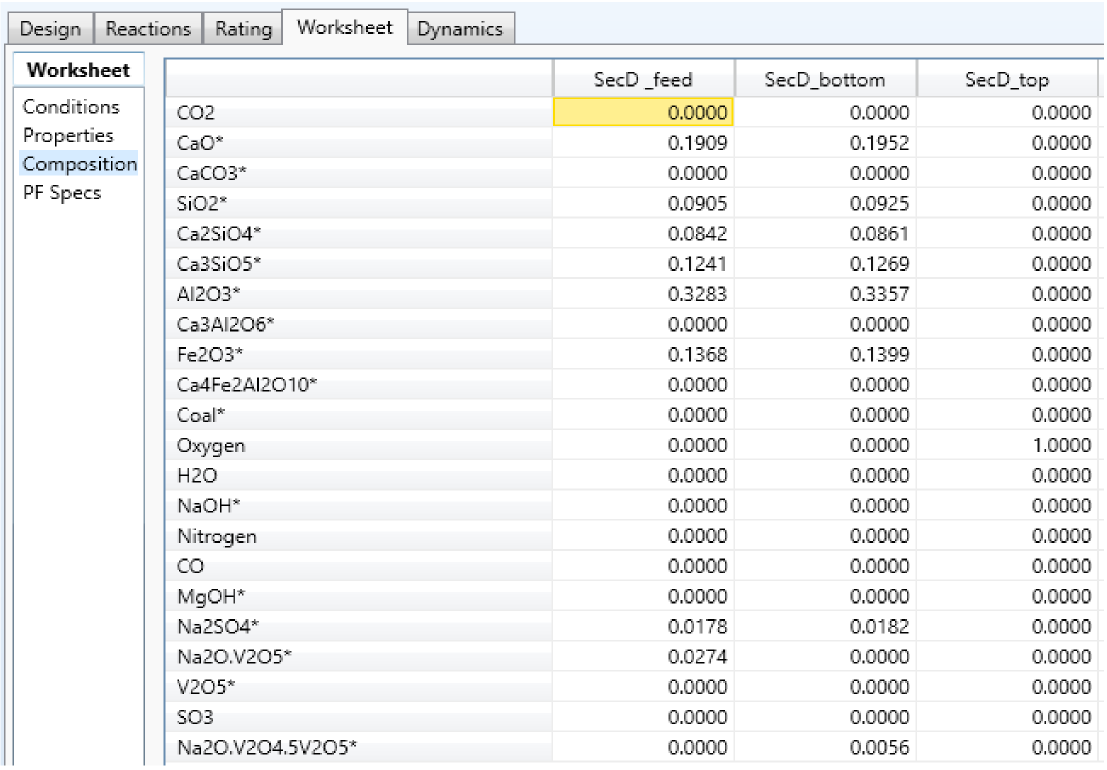
Vessel Volume: 50.00 m3

Liquid Level: 50.00 %

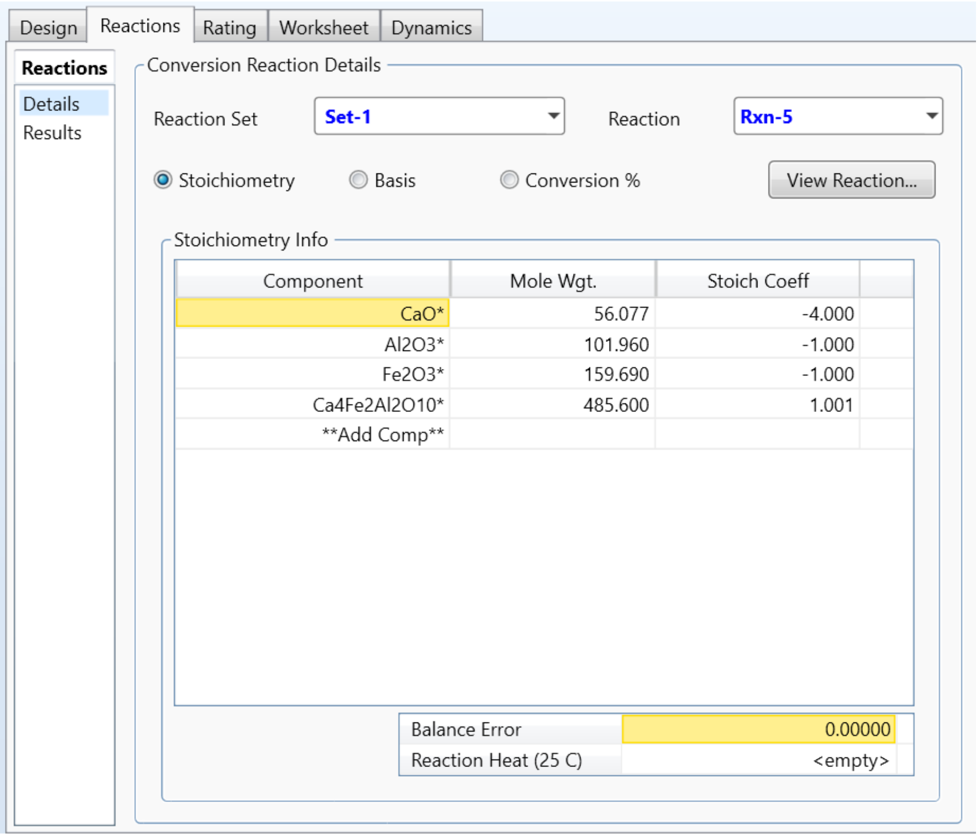
Liquid Volume: 25.00 m3

7.3.5 Final Kiln Reactor Worksheet

Before additive dosing



	SecD _feed	SecD_bottom	SecD_top
CO2	0.0000	0.0000	0.0000
CaO*	0.1909	0.1952	0.0000
CaCO3*	0.0000	0.0000	0.0000
SiO2*	0.0905	0.0925	0.0000
Ca2SiO4*	0.0842	0.0861	0.0000
Ca3SiO5*	0.1241	0.1269	0.0000
Al2O3*	0.3283	0.3357	0.0000
Ca3Al2O6*	0.0000	0.0000	0.0000
Fe2O3*	0.1368	0.1399	0.0000
Ca4Fe2Al2O10*	0.0000	0.0000	0.0000
Coal*	0.0000	0.0000	0.0000
Oxygen	0.0000	0.0000	1.0000
H2O	0.0000	0.0000	0.0000
NaOH*	0.0000	0.0000	0.0000
Nitrogen	0.0000	0.0000	0.0000
CO	0.0000	0.0000	0.0000
MgOH*	0.0000	0.0000	0.0000
Na2SO4*	0.0178	0.0182	0.0000
Na2O.V2O5*	0.0274	0.0000	0.0000
V2O5*	0.0000	0.0000	0.0000
SO3	0.0000	0.0000	0.0000
Na2O.V2O4.5V2O5*	0.0000	0.0056	0.0000



Reaction Set: Set-1

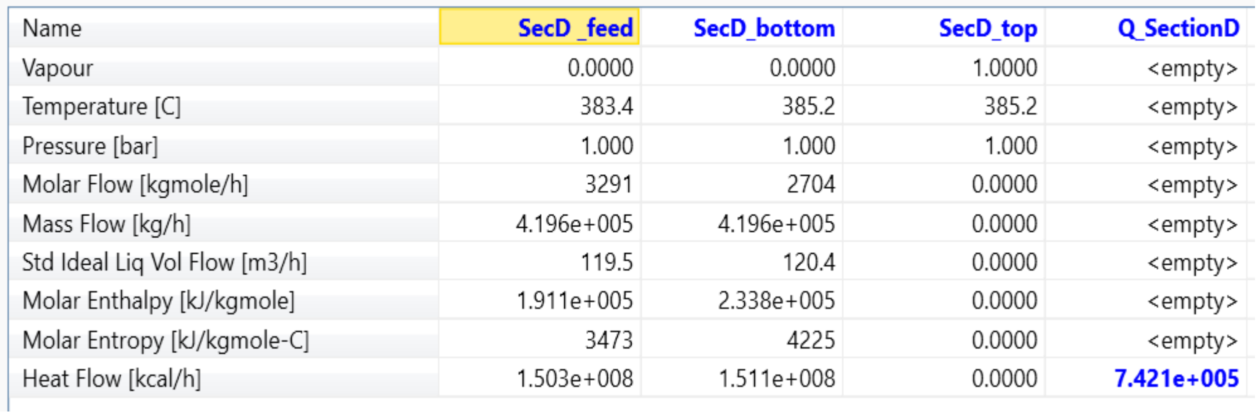
Reaction: Rxn-5

● Stoichiometry ○ Basis ○ Conversion %

Component	Mole Wgt.	Stoich Coeff
CaO*	56.077	-4.000
Al2O3*	101.960	-1.000
Fe2O3*	159.690	-1.000
Ca4Fe2Al2O10*	485.600	1.001
Add Comp		

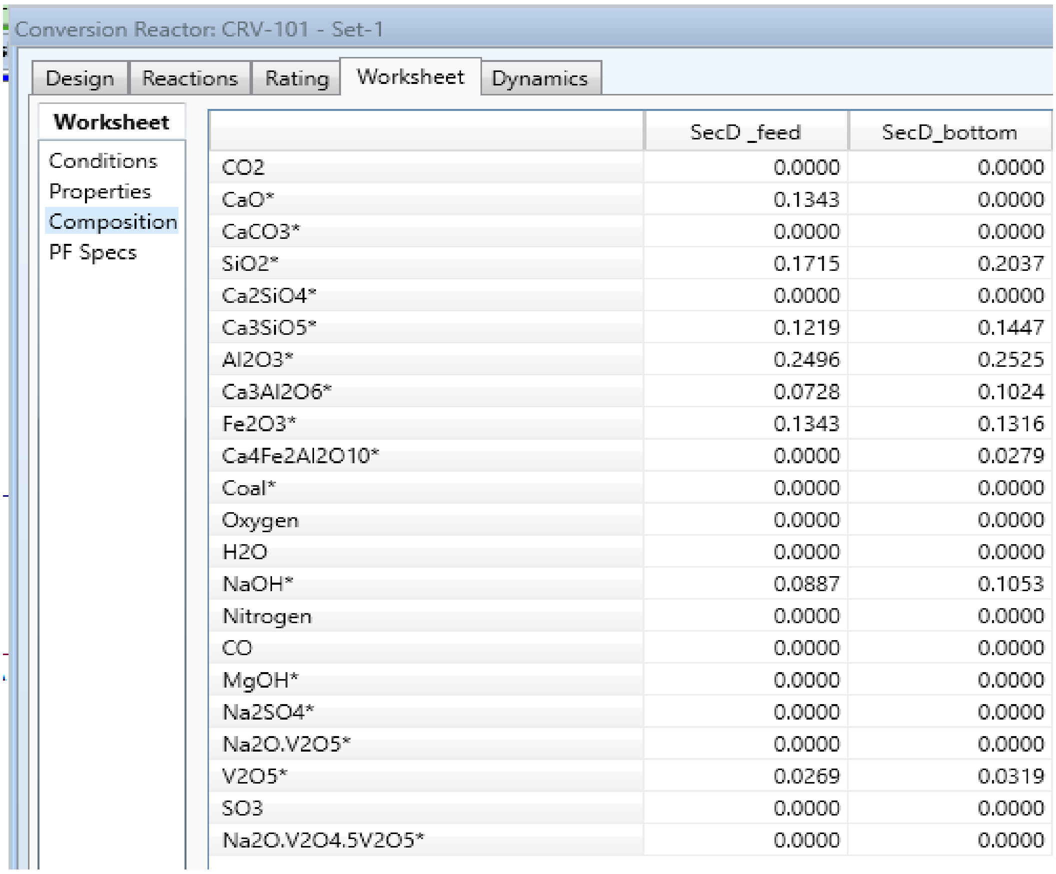
Balance Error: 0.00000

Reaction Heat (25 C): <empty>

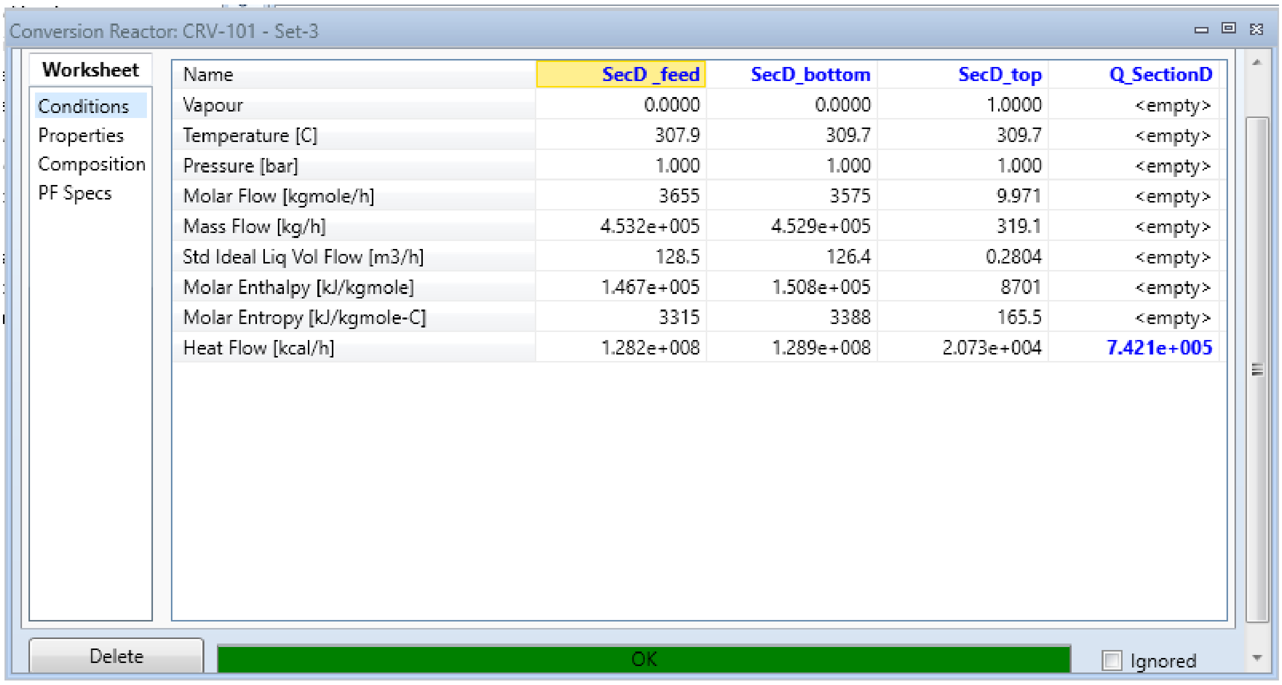


Name	SecD _feed	SecD_bottom	SecD_top	Q_SectionD
Vapour	0.0000	0.0000	1.0000	<empty>
Temperature [C]	383.4	385.2	385.2	<empty>
Pressure [bar]	1.000	1.000	1.000	<empty>
Molar Flow [kgmole/h]	3291	2704	0.0000	<empty>
Mass Flow [kg/h]	4.196e+005	4.196e+005	0.0000	<empty>
Std Ideal Liq Vol Flow [m3/h]	119.5	120.4	0.0000	<empty>
Molar Enthalpy [kJ/kgmole]	1.911e+005	2.338e+005	0.0000	<empty>
Molar Entropy [kJ/kgmole-C]	3473	4225	0.0000	<empty>
Heat Flow [kcal/h]	1.503e+008	1.511e+008	0.0000	**7.421e+005**

After additive dosage



	SecD _feed	SecD_bottom
CO2	0.0000	0.0000
CaO*	0.1343	0.0000
CaCO3*	0.0000	0.0000
SiO2*	0.1715	0.2037
Ca2SiO4*	0.0000	0.0000
Ca3SiO5*	0.1219	0.1447
Al2O3*	0.2496	0.2525
Ca3Al2O6*	0.0728	0.1024
Fe2O3*	0.1343	0.1316
Ca4Fe2Al2O10*	0.0000	0.0279
Coal*	0.0000	0.0000
Oxygen	0.0000	0.0000
H2O	0.0000	0.0000
NaOH*	0.0887	0.1053
Nitrogen	0.0000	0.0000
CO	0.0000	0.0000
MgOH*	0.0000	0.0000
Na2SO4*	0.0000	0.0000
Na2O.V2O5*	0.0000	0.0000
V2O5*	0.0269	0.0319
SO3	0.0000	0.0000
Na2O.V2O4.5V2O5*	0.0000	0.0000



Name	SecD _feed	SecD_bottom	SecD_top	Q_SectionD
Vapour	0.0000	0.0000	1.0000	<empty>
Temperature [C]	307.9	309.7	309.7	<empty>
Pressure [bar]	1.000	1.000	1.000	<empty>
Molar Flow [kgmole/h]	3655	3575	9.971	<empty>
Mass Flow [kg/h]	4.532e+005	4.529e+005	319.1	<empty>
Std Ideal Liq Vol Flow [m3/h]	128.5	126.4	0.2804	<empty>
Molar Enthalpy [kJ/kgmole]	1.467e+005	1.508e+005	8701	<empty>
Molar Entropy [kJ/kgmole-C]	3315	3388	165.5	<empty>
Heat Flow [kcal/h]	1.282e+008	1.289e+008	2.073e+004	7.421e+005

CHAPTER 8

INSTRUMENTATION & PROCESS CONTROL

A control system is a network of computer interfaces and controllers linked together to allow for a coherent overall process like in the industrial production of cement. Therefore, the selection of an efficient control system is paramount to theoverall working of a chemical plant. For this project we have introduced 4 control loops for efficient operation.

We decided to go with a PID conventional control scheme.

A PID controller, which stands for Proportional-Integral-Derivative controller, is a widely used feedback control mechanism in engineering and automation systems. It is designed to regulate a process or system by continuously adjusting an actuator based on the error between the desired setpoint and the measured output. The proportional component responds proportionally to the error, the integral component sums up the past errors to account for steady-state errors, and the derivative component predicts future errors based on the rate of change of the error. By combining these three components, a PID controller can provide stable and accurate control of a wide range of systems, making it a versatile tool in industries such as robotics, manufacturing, and process control.

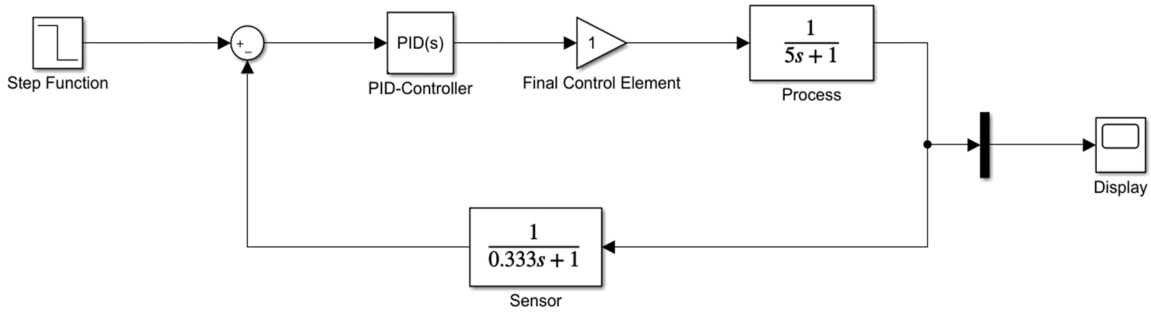


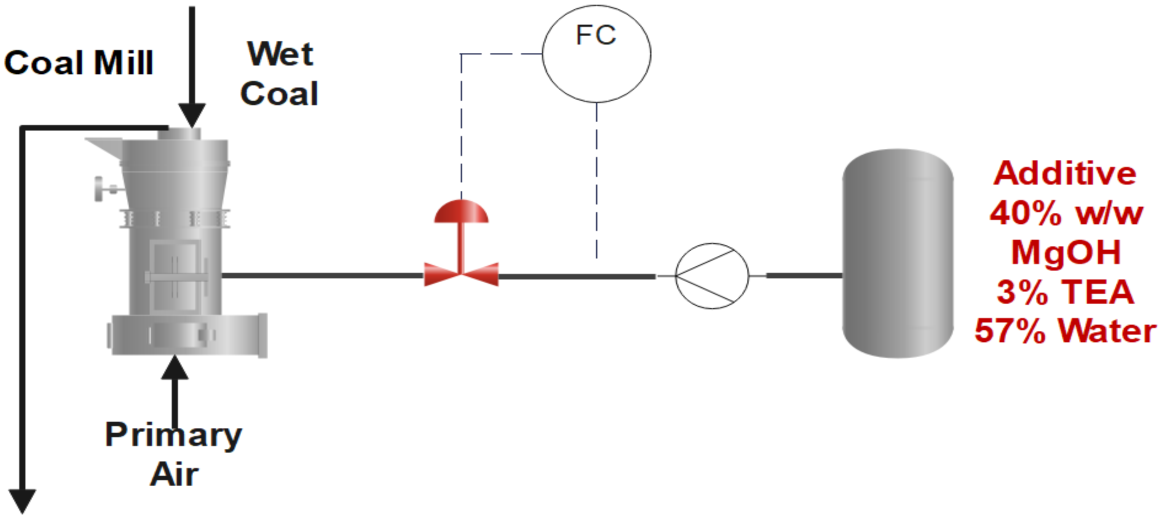
Figure 9 PID loop

8.1 Control Loops

Following are the control loops we used.

8.1.1 Additive Flow Controller

Additive addition should be controlled and specific for proper mixing and usage, for this purpose, we are using a pneumatically controlled flow controller. A flow sensor will measure the flow of the additive which will send the value to the controller in terms of electric signal. The controller compares the value with the set point. In case of any deviation, the controller sends an electric signal to the transducer which converts it into a pneumatic signal for a pneumatically controlled valve to operate accordingly.



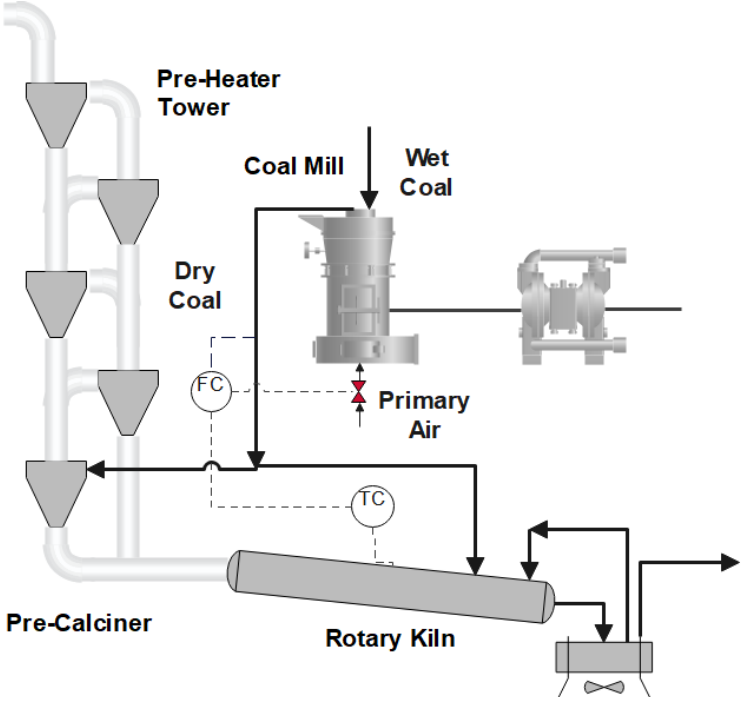
8.1.2 Cascaded Temperature & Flow Control

The control of coal feeding or combustion rate is crucial in maintaining the desired temperature profile within the kiln. This is typically achieved by using a combination of control mechanisms, such as adjusting the coal feed rate, controlling the air supply for combustion, and monitoring the exhaust gas temperature.

A cascade control loop is a control strategy that involves the interconnection of two or more control loops to improve the performance and stability of a system. In a cascade control setup, there is a primary or outer loop and a secondary or inner loop. The primary loop controls the main process variable, while the secondary loop regulates a secondary variable that directly affects the primary variable. The output of the primary loop serves as the setpoint for the secondary loop, allowing it to continuously adjust and fine-tune the control of the secondary variable. We are using temperature and flow control loops.

Primary: Temperature control Loop

Secondary: Flow control Loop



Our control variable is the temperature inside the kiln. Several temperature sensors measure the temperature of the kiln. When the temperature controller receives the signal, it serves as a set point for the secondary loop. The secondary loop having the manipulated variable manipulates the amount of primary air which carries the coal into the kiln for burning. When more coal is burned, it generates a greater amount of heat, leading to an increase in the kiln's internal temperature. Conversely, reducing the amount of coal burned results in less heat being generated, leading to a decrease in temperature.

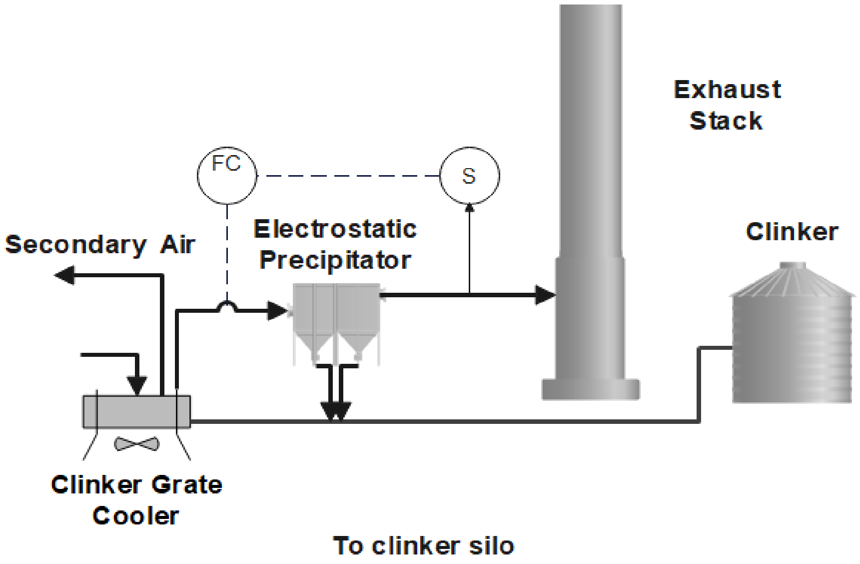
8.1.3 Dust Control

In a cement plant, a dust controller in process and instrumentation refers to a control mechanism that monitors and manages the dust or particulate levels in specific areas or equipment. It typically involves the use of sensors, detectors, and control instruments to measure and control dust concentrations.

These instruments may include dust sensors or particulate matter analyzers that measure the concentration of dust particles in the air. The data collected by these sensors can be used for monitoring purposes or as feedback for an automated control system.

Based on the measured dust levels, a dust controller can activate various mechanisms to control or minimize dust emissions. This may involve adjusting ventilation systems and controlling airflows.

We are using a flow controller for controlling the exhaust from the electrostatic precipitator. A sensor measures the downstream from the precipitator and sends the signal back to the controller to change the airflow according to the requirement.



8.1.4 Level Control

Level control in preheaters and calciners in a cement plant is crucial to ensure the efficient and safe operation of the process. It involves maintaining the appropriate level of material in the equipment to achieve optimal performance.
A Level controller is installed on the pre-heaters. A sensor measures the level and sends back the signal to control the flow of the feed into the preheater.

Equipment	Type	Controlled Variable	Manipulated Variable
Additive Pump	PID	Flowrate of additive towards Coal Mill	Flowrate of additive coming into the Pump
Kiln and Coal Mill		Temperature	Flowrate of Primary Air
Electrostatic Precipitator		Concentration of dust	Flowrate of inlet air
Preheater		Level in preheater	Flowrate of feed into Preheater

CHAPTER 9

ECONOMIC ANALYSIS

Before we conduct the economic analysis of our process, it is worth noting that we have only involved the equipment that we had either proposed and or the major equipment like the coal mill, rotary kiln and additive mill that we have added in the plant. And although we foremost conducted the analysis on Aspen HYSYS itself, using the Economic Analysis mode available, this section for most part portrays calculations that went into this analysis.

Coulson and Richardson Vol.6 [20] was used for the reference tables. The utility amounts were found from Aspen HYSYS and their costs were calculated by using the reference tables already mentioned.

The format of this section evolves the Factorial Method of Cost Evaluation that first requires the purchase costs of individual equipment to be calculated. From this, we calculate the total purchase cost (PCE) from which we can find out the Plant Purchase Cost (PPC) and the Fixed Capital and Working Capital Costs. From the latter two, the total investment required to run the plant (in our case accommodate for the equipment we have suggested or modified) can be calculated.

Another segment of costs is the operating costs which consist of Fixed (Sub-B) and Variable Costs (Sub-A). These already have pre-determined factors that need to be catered to for whatever procedure of events seems relevant to one's process. Variable costs generally comprise Raw Materials and Utilities as well as some miscellaneous costs and the Fixed costs have to do with Maintenance as well costs like Labor and Taxes.

Total Investment

The following section is going to cover the calculation part of our equipment costs, the total plant purchase cost, the fixed and working capital, and then finally the total investment required based on a multitude of factors.

9.1 Purchase Cost of Equipment (PCE)

Now that we have covered the references, let’s move on to the calculations.

1. Rotary Kiln

As there are no tables of indexes for rotary kiln calculations, we have contacted manufacturers and vendors for the cost estimate using our design specifications.
*Purchase cost o*f rotary kiln = 2 M USD

2. Coal Mill

As there are no tables of indexes for coal mills, we have contacted manufacturers and vendors for the cost estimate using our design specifications.
*Purchase cost o*f Coal Mill = 190,000 USD

3. Additive Dosing System

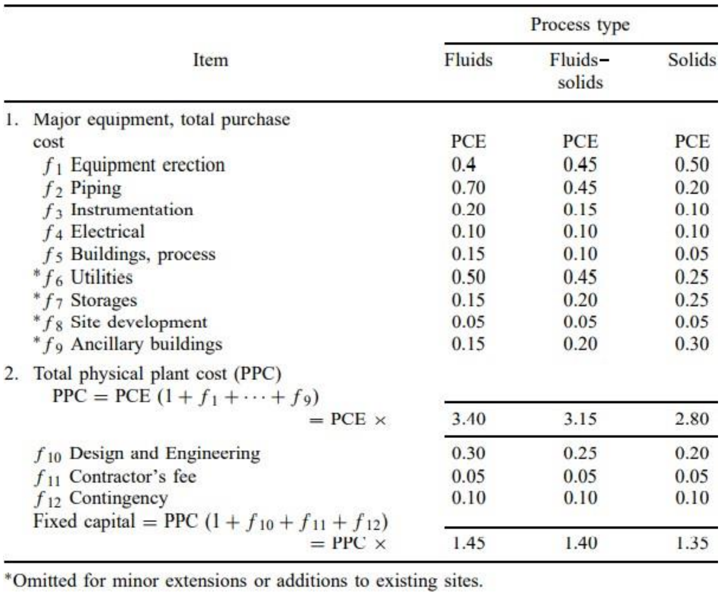
2 Diaphragm pumps = 4000 USD each
Dosing system initial investment = 10000 USD

Total Purchase Cost

Total Purchase Cost (USD 2021) = 2 + 0.19 + 0.01 = 2.2 M USD

9.1.1 Physical Plant Cost (PPC)

The following reference table has been used to calculate costs associated with equipment erection, instrumentation etc.



Item	Process type		
	Fluids	Fluids–solids	Solids
1. Major equipment, total purchase cost	PCE	PCE	PCE
f_1 Equipment erection	0.4	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
*f_6 Utilities	0.50	0.45	0.25
*f_7 Storages	0.15	0.20	0.25
*f_8 Site development	0.05	0.05	0.05
*f_9 Ancillary buildings	0.15	0.20	0.30
2. Total physical plant cost (PPC) $\text{PPC} = \text{PCE}\,(1 + f_1 + \cdots + f_9)$ $= \text{PCE} \times$	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital $= \text{PPC}\,(1 + f_{10} + f_{11} + f_{12})$ $= \text{PPC} \times$	1.45	1.40	1.35

*Omitted for minor extensions or additions to existing sites.

Figure 10 PPC Chart

Table 11 PPC Table

Physical Plant Cost	
Equipment Erection	0.5
Piping	0.2
Instrumentation	0.1
Electrical	0.1
Process	0.05
Storages	0.25
Utilities	0.25
Physical Plant Cost	**$5.39 Million**

Physical plant cost (PPC) = 5.39 M USD

9.2 Fixed capital

Factors used for fixed capital calculation are also in the previous reference table.

Fixed capital = 7.28 M USD

Table 12 Fixed Capital Table

Fixed capital	
Design and Engineering	0.2
Contingencies	0.1
Contractor's fees	0.05
Total	**$ 7.28 million**

9.3 Variable and Operating Costs

The following reference table has been used for calculating the variable and operating costs.

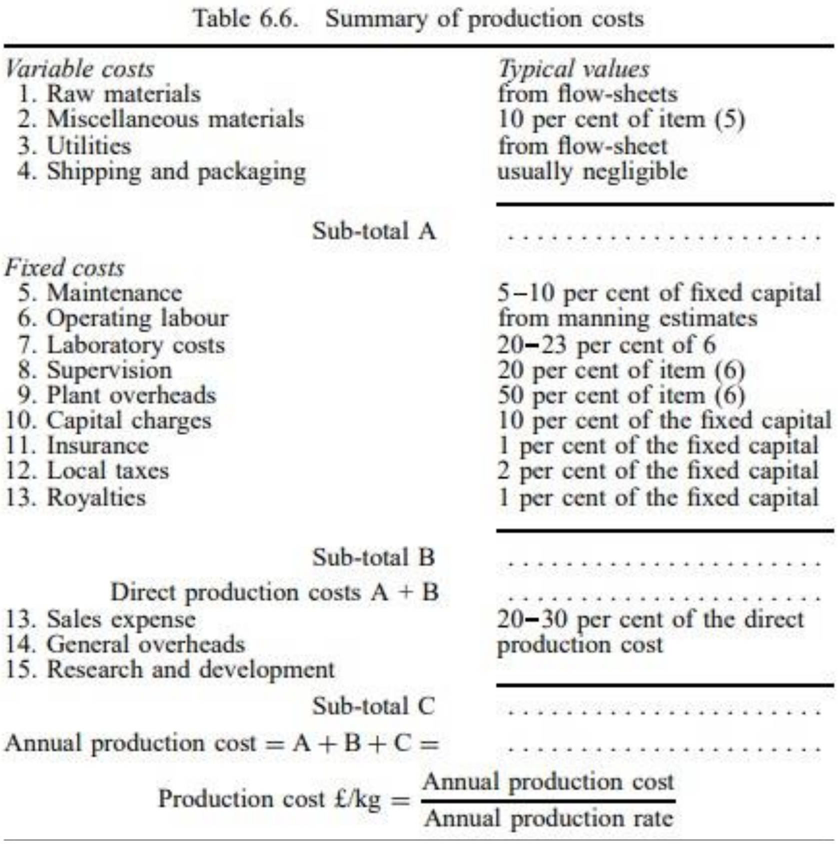


Table 6.6. Summary of production costs

Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	....
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Laboratory costs	20–23 per cent of 6
8. Supervision	20 per cent of item (6)
9. Plant overheads	50 per cent of item (6)
10. Capital charges	10 per cent of the fixed capital
11. Insurance	1 per cent of the fixed capital
12. Local taxes	2 per cent of the fixed capital
13. Royalties	1 per cent of the fixed capital
Sub-total B	....
Direct production costs A + B	....
13. Sales expense	20–30 per cent of the direct production cost
14. General overheads	
15. Research and development	
Sub-total C	....
Annual production cost = A + B + C =	....

$$\text{Production cost £/kg} = \frac{\text{Annual production cost}}{\text{Annual production rate}}$$

Figure 11 Production Cost Table

For variable cost, we use the amount of raw meal feed used in our process per year which is 4.48 M tons/year. Using the composition of cement raw meal which is given as follows:

- 80% limestone
- 15% clay or shale (silica, alumina, iron oxide)
- 5% Iron ore (additional iron oxide)

Using this composition and the prevailing market rates we arrive at the cost of 36 USD/ton of raw meal. Multiplying this with our flow rate gives the following costs:

Table 13 Variable Cost Table

Variable Costs	
Raw material	161.92 M
Miscellaneous	55,000
Utilities	21 M
Total	**$ 182.9255 million**

Table 14 Fixed Cost Table

Fixed Costs	
Maintenance	$ 546000
Operating labour	$ 5 M
Supervision	$ 1 M
Plant Overheads	$ 2.5 M
Capital Charges	$728,000
Insurance	$ 72,800 M
Local Taxes	$ 145,600
Royalties	$ 72,800
Total	**$ 10.06 M**

The cost of modification both in terms of purchase cost of equipment and associated operating costs is shown below. The subsequent table displays the total cost of our modification including our kiln and mill designs and gives a payback period estimate based on production enhancements.

Table 15 Additive Dosing Cost

Additive Dosing	
MgOH based additive flowrate per day	4485.62 kg/day
MgOH based additive cost per day	$6000
MgOH based additive cost per annum	$1920000
Pumps (1 main & 1 standby) diaphragm pumps	$4000 (2 inch diaphragm)
Pressure relief valves (2)	$1000
Dosing controller price	$450
Diaphragm pump operating cost per year	$8847.30
Dosing system initial investment	$5500
Dosing system operating cost per year	$1928847.3

Table 16 Modification Cost

Modification Cost Analysis	
Fixed capital cost	2,200,000 USD
Total investment cost	4,800,000 USD
Annual operating cost	1,980,850 USD
Annual revenue	9,300,000 USD
Annual profit	2,520,000 USD
Payback period	2 years

CHAPTER 10

HAZOP ANALYSIS

HAZOP, or Hazard and Operability Study, serves as a vital research tool for identifying potential hazards that could lead to catastrophic incidents. It finds extensive application across various industries, particularly in the chemical sector, to assess the likelihood of operational problems or hazards occurring within a specific unit or process stream. A multidisciplinary team comprising typically 6 to 12 members, including operations engineers, mechanical engineers, process engineers, electrical engineers, chemical engineers, HSE consultants, and project managers, conducts the HAZOP study. This team employs a critical and analytical approach, dedicating weeks of collaborative effort to comprehensively analyze the unit or stream under investigation.

During the study, the team engages in frequent meetings to discuss and assess all relevant records and parameters that may affect the process's trajectory. The HAZOP study necessitates the examination of multiple Process Flow Diagrams (PFDs) and Piping and Instrumentation Diagrams (P&IDs), which are intricate documents requiring collective effort to decipher. Each unit is individually scrutinized, making the overall process laborious and time-consuming, often extending beyond a month for completion.

Despite the demanding nature of this technique, HAZOP analysis is widely regarded as the most comprehensive and effective approach to proactively address potential issues in a process. Its primary objective is to explore the root causes of failures and implement preventive measures. The study involves meticulously breaking down each unit or process into its smallest components, subjecting them to systematic examination using predefined guide words.

Deviations in terms of temperature, pressure, flow, and composition are rigorously evaluated against relevant guide words to uncover potential hazards.

In summary, conducting a HAZOP analysis in a chemical plant is an essential step towards ensuring safety by comprehensively understanding and mitigating potential process risks.

10.1 Methodology

The HAZOP study encompasses the following procedural steps:

- Develop a comprehensive flow sheet, highlighting the interconnections and units within the process.
- Select a specific unit, such as a kiln or mill, for in-depth analysis.
- Provide a rationale for choosing the selected unit, outlining the factors that make it critical for examination.
- Identify a specific process parameter to focus on during the study.
- Apply the predefined guide words to the chosen process parameter, systematically exploring potential deviations from these guide words as documented in the provided tables.
- Identify potential causes that may lead to deviations and assess the necessity of implementing preventive systems to avert disasters.
- Evaluate the possible outcomes resulting from identified deviations.
- Recommend appropriate preventive measures based on the findings, aiming to mitigate or eliminate potential risks.
- Thoroughly document all relevant data and present comprehensive records of the HAZOP study.

These steps form the basis of conducting a systematic and thorough HAZOP study, facilitating the identification and mitigation of potential hazards in the analyzed process.

10.2 Rotary Kiln

Parameter	Guide Words	Deviation	Causes	Consequences	Recommendations
Fuel flow	No	No fuel		No flame inside kiln	Install and maintain a reliable low fuel alarm system
	Less	Less fuel		Incomplete combustion inside kiln	Install and maintain a reliable low fuel alarm system
	More	Excessive fuel		Waste of fuel	Regularly inspect and clean fuel lines to prevent blockage
Air flow	Less	Less air flow		Flame not propagated	Maintain air flow meters to monitor air supply, Regularly calibrate air flow meters
	More	More air flow		Irregular burning	Install and maintain air flow meters to monitor air supply

10.3 Coal mill

Parameter	Guide Words	Deviation	Causes	Consequences	Recommendations
Coal feed	No	No coal	Absence of fuel	No flame inside kiln	Install and maintain a reliable coal feed interlock system
	Less	Less coal	Insufficient fuel supply	Incomplete combustion inside kiln	Regularly monitor and adjust coal feed rate
	More	More coal	Excessive fuel supply	Waste of fuel	Regularly monitor and adjust coal feed rate
Air flow	Less	Less air	Faulty circulation of air	Excessive moisture in coal	Install and maintain air flow meters to monitor air supply
	More	More air	Lower pressure in system	Coal temperature increased	Install and maintain air flow meters to monitor air supply
Mill temperature	High	Excessive temperature	Higher temperature of coal	Additive properties damaged	Install and maintain temperature sensors to monitor mill temperature
	Low	Insufficient temperature	Excessive moisture	Wet coal goes into kiln	Install and maintain temperature sensors to monitor mill temperature
Coal fines	Accumulation	Excessive coal fines	Formation of coal dust	Wastage of coal in form of dust	Install and maintain a coal fines removal system
Coal dust leakage	Part of	Coal dust leakage	Leakage in coal mill structure	Wastage of fuel	Implement appropriate sealing measures to prevent coal dust leakage

10.4 Pump

Parameter	Guide Words	Deviation	Causes	Consequences	Recommendations
Flow rate	No	No flow	Absence of fuel	Insufficient fluid transfer	Install and maintain flow sensors to monitor flow rate
	Less	Reduced flow rate	Insufficient fuel supply	Insufficient fluid transfer	Regularly monitor and adjust pump speed
	More	Increased flow rate	Excessive fuel supply	Excessive fluid transfer	Control pump speed to maintain desired flow rate
Pressure	Less	Lower pressure	Pump underperforming	Inadequate system performance	Install and maintain pressure sensors to monitor pressure
	More	Higher pressure	Lower pressure in system	Risk of system damage or failure	Install pressure relief valves to protect against overpressure
Temperature	High	Excessive temperature	Higher temperature of additive	Risk of pump overheating or failure	Install and maintain temperature sensors to monitor pump temperature
	Low	Insufficient temperature	Excessive moisture	Risk of fluid freezing	Implement appropriate insulation/heating measures to prevent freezing
Vibration	More	Excessive vibration	Faulty structure	Risk of mechanical failure	Vibration monitoring system
Seal leakage	More	Seal leakage	Faulty seals	Risk of fluid leakage or pump damage	Regularly inspect and maintain seal integrity
Power supply	Less	Power supply failure	Power line damage	Pump shutdown	Implement backup power supply

RESULTS & CONCLUSIONS

Our objective was to optimize high sulfur coal in rotary kiln of cement manufacturing plant. We were to do this while proposing an in-situ solution which did not involve the installation of a new plant or equipment so that cost could be reduced of the modification.

We simulated the entire high sulfur coal optimization process using Aspen Hysys® software. Several conventional, non-conventional, and hypothetical compounds were used as cement manufacturing simulation process is quite unconventional.

The values of proximate and ultimate analysis were experimentally calculated in heterogeneous catalysis lab of SCME, NUST.

The proximate analysis values were as follows:

Table 17 Proximate Analysis

Parameter	**Value**
Fixed moisture	5.3%
Ash content	15.4%
Volatile matter	40.1%
Fixed carbon	39.2%
Total Sulfur	0.23%

The ultimate analysis values were as follows:

Table 18 Ultimate Analysis

Parameter	**Value**
Carbon	65.7%
Hydrogen	5.99%
Nitrogen	1.12%
Oxygen	10.89%

For simulation purposes, the kiln was broken down into a series of conversion reactors. Temperatures gradually increased in each reactor and the products of the previous reactor were introduced as reactants into the following reactor. This way a complete simulation of a typical rotary kiln was carried out.

As shown in the preceding simulation chapter, before the addition of $Mg(OH)_2$ additive, the percentages of ring forming compounds being evolved in the kiln were much greater as compared to after when the additive was dosed.

The application of the additive into the kiln showcased **ring forming compound reduction from 40% to under 5%**.

The proposed solution involved the introduction of novel modifications in the conventional cement manufacturing process.

An additive comprising of $Mg(OH)_2$ was added to the coal mill where it was pulverized with the coal for better mixing and enhanced chemical and physical properties.

The $Mg(OH)_2$ additive flow rate was calculated to be **4485.62 kg/day**. This flow rate of additive was administered to the coal mill through the use of proposed coal mill dosing system which involves the use of diaphragm pumps, dispersion nozzle, pressure relief valves, and process controllers.

Several positive effects were observed due to the addition of the $Mg(OH)_2$ additive.

The primary positive effect is the enhancement in the production of clinker. **Clinker production was projected to be increased by 11.5%.** This change was brought about due to the decrease in ring formation/build-up in kiln and cutting down of kiln shut down hours for cleaning.

The **kiln cleaning hours were reduced by an impressive 50%.** This change was brought about by the addition of the additive which reduced the formation of rings in the kiln. Moreover, previously the kiln was shut down regularly to remove crusts from inside the kiln. Due to our additive, the crusts and rings formation was hindered and hence, the cleaning hours were reduced.

The **Vanadium ppm were reduced from 1890 ppm to 392 ppm**. This improvement was caused due to the addition of the additive which reacted with vanadium compounds instead of allowing the vanadium to go into the kiln and form ring forming compounds.

In conclusion, the additive dosing brought forth profitable results including clinker production enhancement, cleaning hours reduction, and also reduced environmental pollution by capturing vanadium and sulfur sources. The addition of the additive also allows the proposed process to meet **UN SDG 8,9, and 12.**

11.1 Before & After

The following table shows the before/after for the improvements due to additive dosing.

Table 19 Improvements

Process	**Variable**	**Before**	**After**
Additive	Dosage (kg/day)	0	4485.62
Kiln	Clinker production (TPD)	11.5% enhancement in clinker production	
Kiln	Cleaning hours (hours)	>50% reduction in cleaning hours	
Kiln	Vanadium (ppm)	1890	392

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