

Research Article

Parametric Studies of Cement Production Processes

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The cement industry is one of the most intensive energy consumers in the industrial sectors. The energy consumption represents 40% to 60% of production cost. Additionally, the cement industry contributes around 5% to 8% of all man-made CO₂ emissions. Physiochemical and thermochemical reactions involved in cement kilns are still not well understood because of their complexity. The reactions have a decisive influence on energy consumption, environmental degradation, and the cost of cement production. There are technical difficulties in achieving direct measurements of critical process variables in kiln systems. Furthermore, process simulation is used for design, development, analysis, and optimization of processes, when experimental tests are difficult to conduct. Moreover, there are several models for the purpose of studying the use of alternative fuels, cement clinker burning process, phase chemistry, and physical parameters. Nonetheless, most of them do not address real inefficiency taking place in the processes, equipment, and the overall system. This paper presents parametric study results of the four-stage preheater dry Rotary Kiln System (RKS) with a planetary cooler. The RKS at the Mbeya Cement Company (MCC) in Tanzania is used as a case study. The study investigated the effects of varying the RKS parameters against system behaviour, process operation, environment, and energy consumptions. Necessary data for the modelling of the RKS at the MCC plant were obtained either by daily operational measurements or laboratory analyses. The steady-state simulation model of the RKS was carried out through the Aspen Plus software. The simulation results were successfully validated using real operating data. Predictions from parametric studies suggest that monitoring and regulating exhaust gases could improve combustion efficiency, which, in turn, leads to conserving fuels and lowering production costs. Composition of exhaust gases also depends both on the type of fuel used and the amount of combustion air. The volume of exit flue gases depends on the amount of combustion air and infiltrating air in the RKS. The results obtained from the study suggest a potential of coal saving at a minimum of about $\dot{m}_{\text{coal}} = 1263 \text{ kg} \cdot \text{h}^{-1}$, which approximates to 76,126 tons per year at the current kiln feed of $58,000 \text{ kg} \cdot \text{h}^{-1}$. Thus, this translates to a specific energy saving of about $1849.12 \text{ kJ} \cdot \text{kgcl}^{-1}$, with relatively higher clinker throughput. In this vein, process modelling provides effective, safe, and economical ways for assessing the performance of the RKS.

1. Introduction

There are several process parameters in a cement rotary kiln system, which should be studied in order to observe trends that may indicate problems and provide necessary mean data for process analysis. The most important kiln controlling parameters are clinker production rate, fuel flow rate, specific heat consumption, secondary air temperature, kiln feed-end temperature, preheater exhaust gas temperature, ID fan pressure drop, kiln feed-end percentage oxygen, percentage downcomer oxygen, primary air flow rate, specific kiln volume loading, specific heat loading of burning zone cross-section area, and cooler air flow rate including temperature,

pressure, and oxygen profile of the preheater [1–4]. However, the principal control variables are burning zone solid material temperature typically aimed at $T_{\text{brn}} = 1500^\circ\text{C}$; feed-end gas temperature typical at $T_{\text{brn}} = 1000^\circ\text{C}$; and feed-end oxygen typical at 2% [1]. Control is managed by adjustments of kiln feed, fuel flow rate, and ID fan speed [1].

A process simulation software is used for the description of different processes in flow diagrams. The objectives of simulation models are to deliver a comprehensive report of material and energy streams, determine the correlation between the reaction and separation systems, study how to eliminate wastes and prevent environmental pollution, evaluate plant flexibility to changes in feedstock or product policy,

investigate the formation and separation of by-products and impurities, optimize the economic performance of the plant, validate the process instrumentation, and enhance process safety and control.

Cement production processes involve complex chemical and physical reactions during the conversion of raw materials to the final product. Moreover, the clinker burning process, which has a decisive influence on energy consumption and the cost of cement production, involves the combustion reaction of fossil fuel and a complex heat exchange between solids from raw materials and hot combustion gases [2, 3]. It also involves mixing, as well as separation of solid and fluids at various compositions, temperatures, and pressures. Therefore, following these complex issues which contribute to the inefficient energy use and emissions in cement kiln systems, there is a strong need to use computer-aided modelling to simplify the work of analyses. Other studies have tried to vary fuel properties, primary- and secondary air settings, and fuel feed location to study the effect of the operational setting on refuse-derived fuel, where the results show a good applicability of the presented modelling procedure [2–5].

Cement manufacturing is a high volume and energy intensive process, and according to the authors in [6, 7], the price of consuming large amounts of nonrenewable resources and energy (principally thermal fuels and electrical power) in those plants contributes to about 40% to 60% of the total manufacturing cost. In addition, the cement plants are also intensive in terms of CO₂ and other effluent emissions. For that reason, sustainability can be viewed as a broad and complex concept in the cement industry sector, as it includes a variety of key issues, such as (i) efficiency of resource and energy use, (ii) reduced emissions, (iii) health and safety protection, and (iv) competitiveness and profitability, which are essential for its economic survival and social acceptance [8].

The term “cement” includes a range of substances utilized as binders or adhesives, even though the cement produced in the greatest volume and most widely used in concrete for construction is Portland cement. Cement plants basically consist of three manufacturing parts: (i) raw material and fuel supply preparation, (ii) clinker production (commonly named as the pyroprocessing part), and (iii) intergrinding and blending of cement clinker with other active ingredients to produce the required types of cement.

The cement manufacturing process starts by handling a mix of raw materials: (i) naturally occurring limestone, which is the source of calcium, (ii) clay minerals and (iii) sand, which are the sources of silicon and aluminium, and (iv) iron-containing components. The raw materials are ground and mixed together in controlled proportions to form a homogeneous blend, termed as a raw meal or raw-mix, with the required chemical composition.

Raw meal is then subjected to the continuous, high temperature operations in the pyroprocessing part of the plant, namely the rotary kiln system (RKS). The progressive increase of temperature along RKS initiates a series of consecutive reactions of raw meal, ranging from the evaporation of free water to the decomposition of raw materials and the combination of lime and clay oxides. This means that raw meal passes through a series of functional zones where it is

dried, preheated, calcined, and sintered to produce clinker minerals, which, in turn, form the semifused pellets of cement clinker. Regarding the type of pyroprocessing employed in RKS, the overall technology for cement production can be roughly divided into (i) the dry process, (ii) the wet process and its modification, (iii) the semidry process, and (iv) the semiwet process. Each of the enumerated processes are characterized by different raw material preparations and different configurations of RKS, and in practice, they have to be selected according to consideration given to properties of raw materials and costs of fuel and electricity, as well as conditions of location, etc. The major technologies in use today, including their configurations, respective temperature, and functional zones inside the RKS, are illustrated in Figure 1 [9–11].

Generally, although the wet processes are more energy intensive due to the evaporation of high moisture contained in raw materials, the investment cost of those plants is rather low and high-quality products are manufactured easily [12–16]. On the other hand, the plants based on the dry processes consume less energy, which results in much lower operational costs of manufacturing. However, since the progress of technology almost eliminates the differences in final quality products between technologies and as the need for energy conservation is getting increasingly stronger, in the future, the wet process will not necessarily be required. Currently, all cement plants in Tanzania use the technology based on the dry process.

In the final stage of production, Portland cement is produced by intergrinding cement clinker with sulphates such as gypsum and anhydrite in order to obtain a fine homogeneous powder. In blended (composite) cements, there are other constituents such as artificial pozzolana, sand, limestone, granulated blast furnace slag, fly ash, and natural or inert fillers. These are interground with the cement clinker or may need to be dried and ground separately. The kind of cement intergrinding and blending process and the corresponding plant concept, chosen at a specific site, depend on the cement type to be produced, with special importance of the grindability, humidity, and the abrasive behaviour of its compounds. Sometimes, those processes may be performed at the plants that are in separate locations from the clinker production plants. About 70% of the total energy required for cement productions is thermal energy, and 30% is used as electrical energy [9], in which the pyroprocessing part of the plant (RKS) takes around 90% of the total energy consumption. Most of the thermal heat losses occur in the same part of the plant, due to temperature variations of the feed solid streams caused by chemical reactions, as well as the heat exchange with hot flue gases (in the heating section of RKS) and ambient air streams (in the cooling section of RKS) [17–19]. Some authors pointed out that those heat losses can lead to up to 20% of initial energy wastage [20].

Cement production also has a significant contribution to environmental degradation originating both from anthropogenic pollutant emissions and mining activities of raw materials and coal, which is the most usual source of energy in the cement plant. In this way, it contributes to about 5 to 8% of anthropogenic GHG emissions [13, 14, 21]. These emissions

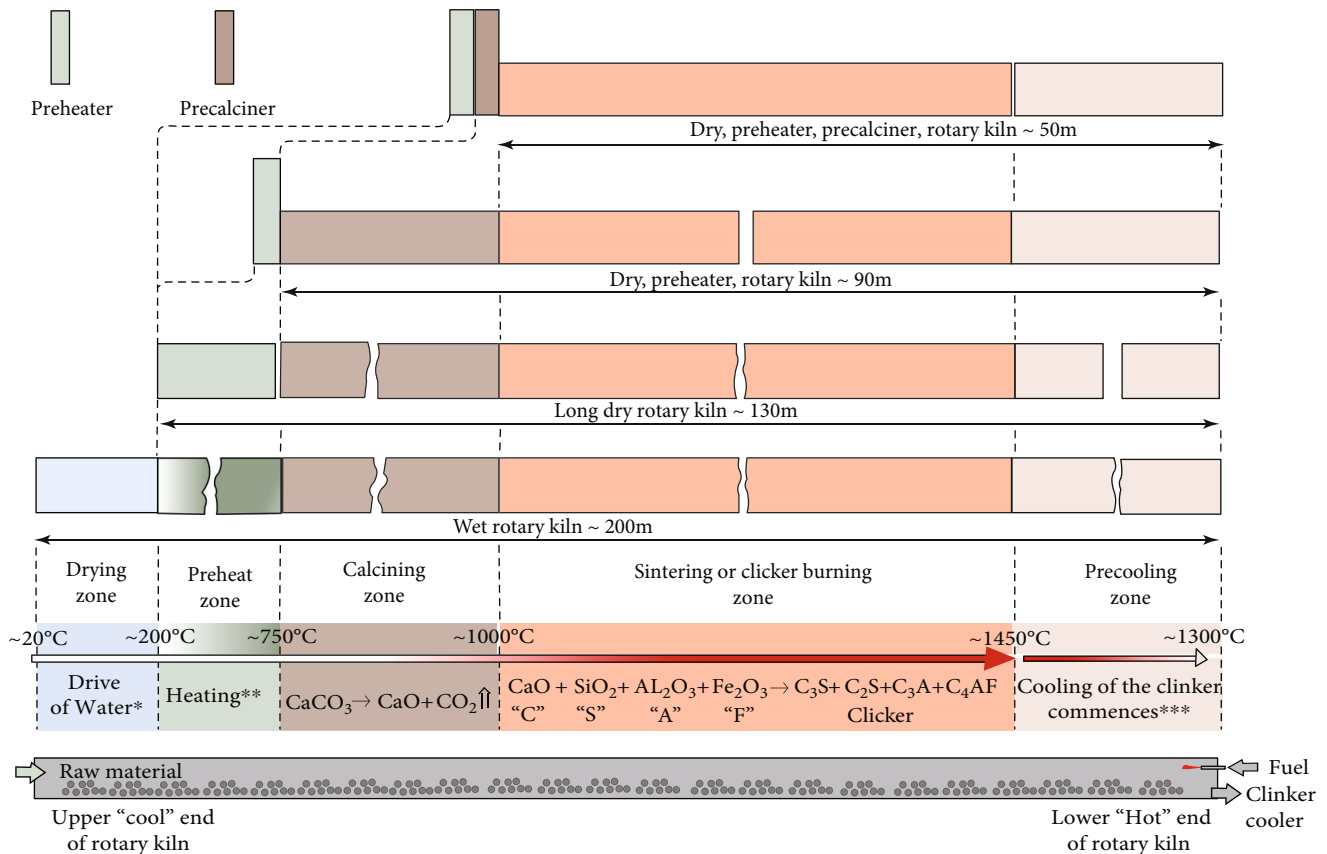


FIGURE 1: Most important technologies for clinker (cement) production in regard to RKS configuration, temperature ranges, and functional zones [9, 10]. *Escape of liquid and adsorbed water. **Dehydration of clay minerals and activation of oxides by decomposition of clay minerals. ***The length of this zone and the cooling rate depend on the primary burner position and the type of cooler. The clinker leaves the rotary kiln (a) at a temperature of about 1350°C when the sintering zone is close to the RK exit and (b) at a temperature of about 1150°C when it is a long cooling zone for satellite coolers.

have two main sources, which are both located in the RKS: (i) process CO₂ released by the calcination of carbonate minerals (about 62% of the total direct CO₂ emissions) and (ii) energy-derived CO₂ released by the combustion of fuels used in the clinker production (about 38% of the total direct CO₂) [22].

Many studies have evaluated energy and environmental performance of the cement manufacturing plants worldwide. Farag and Taghian [23] investigated the energy performance of five Egyptian cement plants, where according to them, the energy efficiency varied between 41.6% and 55.5%. Gürtürk and Oztop [24] investigated the thermal performance of a plaster production plant, whereby the energy efficiency of RKS was 69%. A similar investigation was conducted by Parmar et al. [25], where the energy efficiency of RKS was 51.90%. Kolip and Savas [26] analysed the RKS with a four-stage cyclone preheater and with a precalciner and reported first and second law efficiencies of 51% and 28%, respectively. Koroneos et al. in [27] examined cement production in Greece using energy and exergy analysis, and their results uncovered that the energy efficiency of a typical RKS was 68.8%. Furthermore, their results indicated that the biggest thermal energy losses in the plant were due to irreversibility, which occurred during the preheating of feed, the cooling of

clinker, and the combustion of pet coke. The energy efficiency of a raw material preparation unit of 84.30% in a cement plant in Turkey was calculated by Utlu et al. in [28], while Atmaca and Yumrutas in [29] conducted exergoeconomic analysis of a 4-stage dry rotary cement plant and found that the overall energy efficiency of the plant was 59.37%. Evaluation results of the thermal performance of a clinker grate cooler system was undertaken by Madlool et al. [30], who found that the energy efficiency varied between 46.18% and 45.19%. The influence of calcium oxide formation, CO₂ emissions, and environmental effects of pyroprocessing in an RKS was studied by Boyaghchi in [31]. The energy performance of processes in lime vertical shaft kilns was conducted by Gutiérrez et al. in [32] and in a cement trass mill by Sogut et al. in [33]. Rasul et al. in [34] investigated the use of energy recovery systems in Indonesia's cement plants and reported that energy efficiency could be significantly improved. In their calculations, clinker burning efficiency was 52.07% and cooler efficiency was 47.75%.

In their recently published paper, Rahman et al. [35] pointed out four commercial software packages, namely, Aspen Plus, Aspen HYSYS, ANSYS Fluent, and CHEMCAD, as the commonly used computer-aided modelling and simulation tools in cement manufacturing processes. The authors

observed that most of the studies concerning modelling and simulation of cement manufacturing processes that can be found in the literature are based on computational fluid dynamics (CFD) and use the ANSYS Fluent package. This software allows the modelling of the effect of surface condition and phase changes of the material, as well as the optimization of fluid flow, material feed, and containing structure [2–5]. Furthermore, by considering the nature of cement production, specific needs and purpose of conceptual process design, and research experience from the other authors [36–39], they identified the Aspen Plus software as the most suitable tool for flow sheeting modelling and simulation of cement plants. Aspen Plus uses a flow sheet simulator to graphically represent each stage of the process and enable quick and easy alterations to a process, without requiring a new model for each change. In addition, the Aspen Plus software has a rich database and has the ability to simulate chemical reactions within solid, liquid, and vapour phases. For that reason, the Aspen Plus software is used in this study for modelling and simulating the MCC plant, focusing on the clinker chemistry and thermodynamics in RKS.

In cement production processes, there are several models for the purpose of studying the use of alternative fuels [4, 36, 39]: phase chemistry [40], oxidation process of coal tar pitch [41], cement raw material blending process [42], reduction of CO₂ [43], sensitivity analysis of a model used for the design of rotary kiln processes [44], and a nonlinear model predictive control [45]. However, all these models do not address issues of real inefficiency taking place in cement production processes, equipment, and the overall system. Most models found in the literature are based on the first law of thermodynamics alone, thereby giving no insights into minimizations of irreversibility due to chemical reactions. Furthermore, it has been very difficult to simulate processes which include thermodynamic properties of fluids and solids in the same simulating environment software. Therefore, the current study sheds light on providing a model which combines both solids and fluids in the same simulating environment for the purpose of improving the performance of cement production processes in the kiln system. The study provides a model that deals specifically with the optimization of energy use in cement production processes using both first and second laws of thermodynamics. With due regard, the developed model was advanced by making use of exergy analysis, so as to identify inefficient processes and components within the system [46]. The thermodynamic model of RKS developed is not only used to calculate the energy and environmental indicators of RKS, but to also provide a useful clue for reducing energy consumption, as well as predict the system behaviour under alternative configurations and different production parameters. In this work, parametric analysis studies were conducted with a view to investigate the effect of varying the kiln system parameters to the system behaviour, process operation, environment, and energy use while maintaining the quality of clinker produced within acceptable values. The aim was also to arrive at a kiln system which performs better in terms of energy use and environmental conservation. Parametric analyses were carried out by varying coal flow rate, as well as cooling and primary air

flow rates. Other comparative parametric analyses carried out were temperature versus fuel flow rate, fuel flow rate versus composition of combustion gases, fuel flow rate versus exhaust gas composition, coal moisture content versus combustion efficiency, and air flow rate versus exhaust gas composition.

The rest of the paper is organized as follows: the whole production process in the MCC is described in Section 2. The process is illustrated by a simplified block flow diagram, where the most important technological operations are presented as interrelated subsystems. In Subsection 2.2, key issues related to the modelling of RKS in Aspen Plus software are presented and discussed. Subsection 2.3 reports the simulation results and validation. Section 3 presents parametric study results of the kiln system using the model with respect to the key material and thermodynamic parameters in RKS. Section 4 is devoted to the general conclusion of research presented in this paper and directions for future works.

2. The Case Study

This paper presents the parametric study results of the MCC four-stage preheater dry rotary kiln system with a planetary cooler [46] built in the Mbeya region of Tanzania in 1978. The plant current production capacity is about 770 tons of cement per day, and it has been growing dramatically during recent years as a result of the growing demand for cement in the country. The cement production in the MCC plant is based on the dry process technology, and according to the preliminary energy audit, the thermal energy consumption in MCC is about 3.5 GJ per ton of produced clinker. The main source of energy in the plant is the coal that is obtained from Tanzania (Tancoal) and from Malawi (both, Mchenga and Erland). The major product of MCC is composite, pozzolana cement, while the ordinary Portland cement is a minor product.

The energy performance of most existing cement manufacturing plants in Tanzania is similar to the other plants in sub-Saharan Africa (SSA), and it is low when compared to the average global available best practice. Studies indicate that the specific electrical energy consumption in some cement plants in East and Central Africa varied between 105 kWh and 140 kWh per ton of produced cement, where the specific thermal energy consumption is between 3.35 GJ and 4.19 GJ per ton of produced clinker [47]. Obviously, this is very far when compared to the typical plants of India, for instance, where the specific electrical energy consumption is about 85 kWh per ton of produced cement, where the specific thermal energy consumption is usually less than 3.18 GJ per ton of produced clinker.

During the preliminary energy audit in the MCC plant, it was observed that the energy performance of the plant is more than 20% lower compared to similar plants in other parts of the world. For this reason, the goal of the study presented in this paper is to identify process improvement opportunities which could increase sustainability indicators of the cement production process in the plant. The research was performed by modern computer-aided modelling and simulation tools which were also used for comprehensive energy analysis of RKS. As it was mentioned before, this part

electrostatic precipitators, which are presented as exhaust gas cleaning units (EGCL unit and EGCn unit). In EGCL, the hot flue gases are cleaned from the dust particles originating from raw materials or coal, while in EGCn they are cooled to a suitable temperature before they are released to the environment.

The raw meal from PH is then transferred to the next subsystem, the rotary kiln (RK), which is a highly refractory-lined cylindrical steel shell (3.95 m dia, 58 m long), inclined at an angle of 3% and equipped with an electrical drive to rotate at 1.5 rpm. It is a countercurrent heating device, whereby its inclination facilitates a continuous transport, so that preheated Rm_x , fed into the upper end, travels slowly by gravity, to be discharged as a clinker into the clinker cooler (CC) at the lower discharge end. During the process, the rotary movement enables a continuous rolling motion of the solid material and helps to create the clinker pellets (Cl_p). The combustion of coal in burners, at the firing end of RK, produces a current of hot flue gases that initiate the clinker burning process. The temperature of the Hfg in RK depends on the volume flow rate and temperature of cooling air (Ca), primary air (Pa), and secondary air (Sa) and is usually regulated by the temperature of secondary air (Sa). Before the use in RK, the raw coal feed (Fl_r) passes the fuel preparation subsystem (FP), where it is pulverized and preheated. The pulverization of coal is performed in the coal mill, while the hot flue gasses from PH (Hfg_4) are used for preheating and drying of the raw coal. The stream of preheated coal (Fl_{ph}) is then transferred into the rotary kiln burner.

A planetary clinker cooler (CC) is used to cool down the clinker from approximately 1400°C to 100°C. The planetary cooler is a set of tubes (9 to 11) fixed to the kiln and without a separate drive. Cooling of the clinker starts in the RK cooling zone which is created 1.5 m to 2.5 m behind a flame. The heat exchange between the hot clinker (Cl_p) and cooling air (Ca) in a CC takes place countercurrently and maintains a minimum cooling velocity in order to avoid unfavourable mineralogical clinker phases and crystal sizes. During the energy audit, it is observed that a considerable amount of thermal energy is transferred to the environment since approximately three quarters of the cooler shell is not insulated. The cooled clinker material stream (Cl_{co}) which passes the CC is then transferred to the subsystem named the cement mill (CM), where it is ground and blended with additives such as gypsum (Gy) and pozzolana (Pz) to form the cement (Cm). From Figure 2, it can be noted that the boundary of RKS considered in this study involved three major subsystems: the preheater tower (PH), the rotary kiln (RK), and the clinker cooler (CC). Other subsystems, as well as facilities such as storing, packaging, logistics, offices, laboratory, and transport are not considered, due to the fact that they are not intrinsic or specific for the cement manufacturing processes [51].

2.2. Modelling and Simulating RKS in Aspen Plus Software. In this section, a description of the model that is used for the simulation of RKS is presented [46]. The discussion is supported by a flow sheet of a research object created by Aspen

Plus software and presented in Figure 3 and by a generalized summary of all Aspen unit operation models used in the modelling process presented in Table 1. The simulation model was considered as a steady state control volume system with steady flow processes that operate in a direct mode and under the following assumptions:

- (i) Variations of potential and kinetic energies were neglected
- (ii) Pressure drops were considered only for the preheater tower cyclone simulation
- (iii) All gas streams were assumed to be ideal gases
- (iv) The raw material feed and coal particles were considered as homogeneous
- (v) Reactors operated in adiabatic and uniform conditions, and all outlet streams left the reactors at the same temperature
- (vi) Chemical equilibrium was assumed for all chemical reactions within the system
- (vii) Thirty percent of calcination was considered to take place at the last stage of the cyclone preheater tower

The calculations were performed under the following assumptions: (i) cyclone efficiency was selected from the range of 95% to 75%, and a corresponding pressure drop in cyclones were in the range of 1.51 mbar to 0.83 mbar, respectively; (ii) PH-stage mixed pressure drops were set to 0.8195 bar, 0.8390 bar, 0.8514 bar, and 0.8170 bar; (iii) isentropic and mechanical efficiency of ID-FAN was assumed to be 85%, and in the case of a cooling air fan it was 75%; (iv) pressure drops in EGCL and EGCn were set to the values of 21 mbar and 50 mbar, respectively; and (v) the minimal available temperature difference in CC was set to 15°C.

The IDEAL property method in Aspen Plus software was considered as a good choice for the RKS simulation, since the process involves conventional components (such as H_2O (g), N_2 (g), and O_2 (g)) at low pressure and high temperature. For nonconventional and heterogeneous components (like coal), the HCOALGEN and DCOALIGT models were employed. For hot flue gas streams, a combination of mixed conventional inert nonconventional particle size distribution (MCINCPD) was used. The choice was suitable since the simulation includes CISOLID and NCPSD solid with particle size distributions, as well as conventional components. Defining substream NCPSD allowed the inclusion of component attributes such as proximate analysis (PROXANA), ultimate analysis (ULTANAL), and sulfur analysis (SULFANAL) for coal combustion.

Combustion processes in the rotary kiln burner at MCC was modelled by using the Aspen unit operation model RGibbs. The same unit operation model was also chosen for chemical reactions in pyroprocessing, because it was the only model that can calculate phase and chemical equilibrium between solid solutions, liquids, and gases. It was assumed that 30% of the calcination process takes place at the final stage of the preheater cyclone, and the remaining

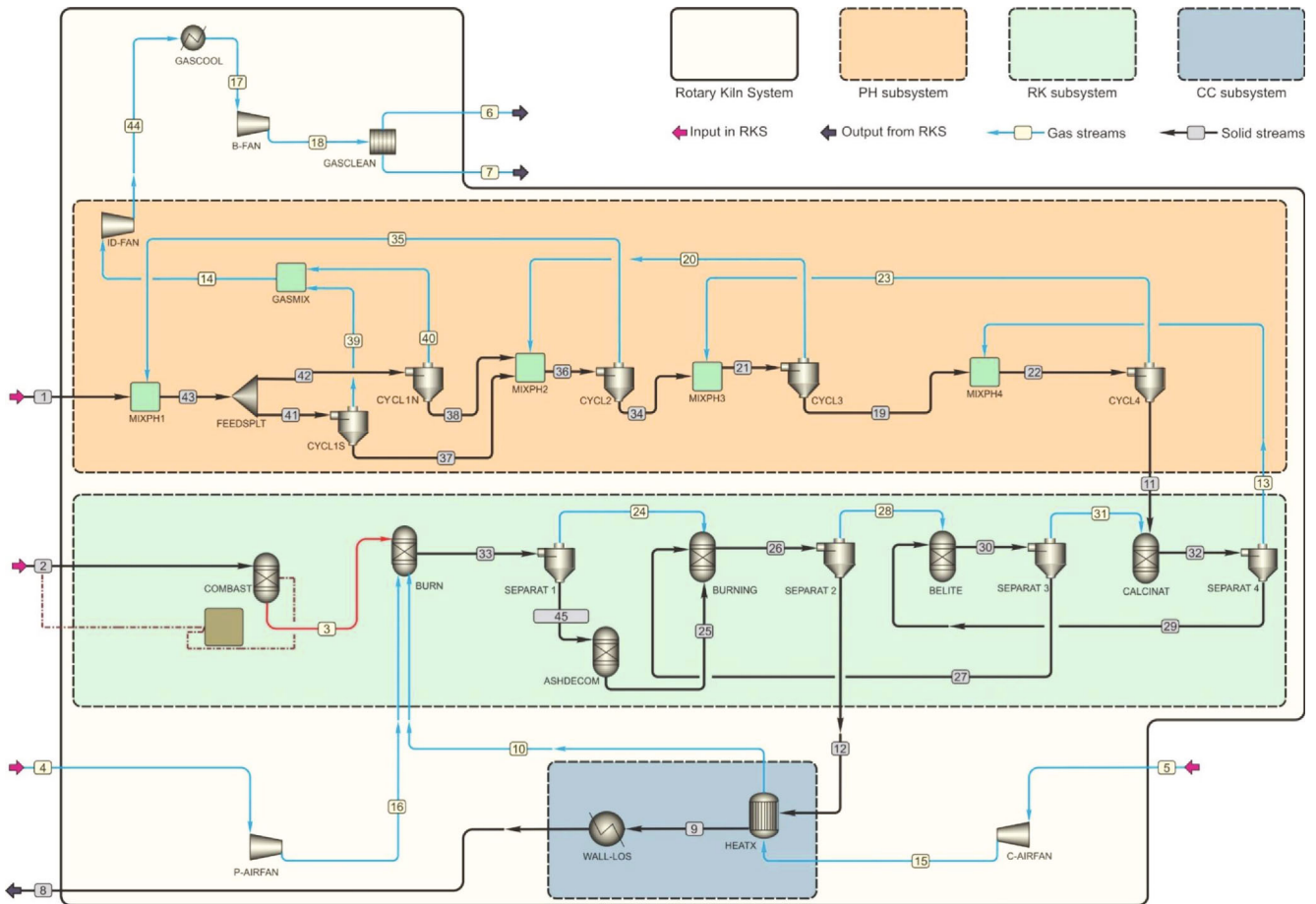


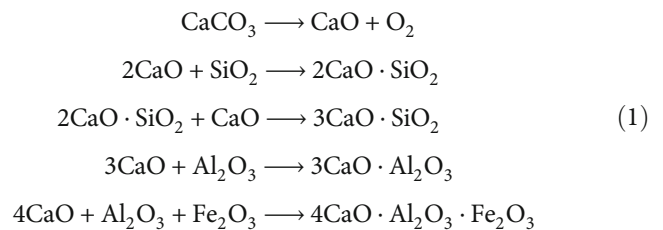
FIGURE 3: Flowsheet of RKS created by Aspen Plus software.

70% was carried out in a Gibbs reactor. The planetary cooler was simulated using a countercurrent two-stream heat exchanger model (HeatX), and heat losses through the cooler shell were modelled using the Heater model. Cooling air was drawn into the COOLER by a cooling air fan (model Compr) in a countercurrent direction with the incoming hot clinker.

Each of the preheater stage cyclones were modelled using the combination of cyclones and RGibbs model blocks, except for the 4th stage, whereby combinations of the Cyclone and RStoic models were used. The 4-stage preheater models were connected in a series with Cyclone models (removal of large particles) and FabFl models (removal of smaller particles). The cyclones were specified by using a design mode, where the efficiency correlation used was the Shepherd and Lapple model and the type was set to medium efficiency. The simulation of the 4-stage PH starts with the injection of raw meal to the mixer (the RGibbs model), which represents a 1st-stage riser duct. Furthermore, hot exhaust gases from RK entered the PH through the rotary kiln riser duct. The purpose of splitting stream 43 was to control the pressure drop in the 1st-stage preheater cyclones by reducing the mass flow rates inside the cyclones. When the plant is in compound operation, precleaned gases (stream 44) are directed to the raw mill for raw meal drying. However, when the raw mill was off, precleaned exhaust gases were fed to the

cooling tower (the Heater model), where they were cooled down. The booster fan was used to draw out cooled precleaned gas from the cooling tower to the Bag Filter (the FabFl model), where it was further cleaned. The clean gas stream 6 was finally drawn out by fan to the environment. The residue solid (stream 7) could be directed to the raw mill depending on its chemical composition.

Simulation of the kiln system in this study considered the following chemical reactions for the processes of clinker formation:



The fuel specific heat energy consumption was calculated as follows:

$$q = \frac{\dot{m}_f \cdot \text{HHV}}{\dot{m}_d}, \tag{2}$$

TABLE 1: Aspen Plus unit operation models in RKS.

Aspen Plus unit operation model	Flow sheet component in Figure 3	Specification and function
RGibbs	CALCINAT	Completion of calcination
	BURN	Coal combustion (streams 3, 16, and 10)
	BURNING	Clinker burning (streams 27 and 26)
	BELITE	Formation of belite (C ₂ S) (stream 29)
	MIXPH1	Mixing of solids (stream 1) with gases (stream 35) and drying of free water from raw meal
	MIXPH2	Mixing of solids (streams 37 and 38) with gases (stream 20) and evolution of combined water from raw meal
	MIXPH3	Mixing of solids (stream 34) and gases (stream 23) and evolution of combined water from raw meal
	GASMIX	Combining gases (streams 41 and 42)
RStoic	MIXPH4	Precalcination of 30% of limestone
RYield	DECOMP	Decomposing coal (stream 2)
	ASHDECOM	Decomposing ash (stream 45)
Cyclone	CYCL4	Separates solids (stream 11) from gases (stream 23)
	CYCL1N	Precleaning of exhaust gases (stream 42)
	CYCL1S	Precleaning of exhaust gases (stream 41)
	CYCL2	Precleaning of exhaust gases (stream 36)
	CYCL3	Precleaning of exhaust gases (stream 21)
	SEPARAT4	Separates gases (stream 13) and solids (stream 29) of calcination products
HeatX	COOLER	Cooling clinker (stream 12)
Heater	WALL-LOS	Set thermodynamic conditions of streams 8 and 9 to quantify cooler losses
	GASCOOL	Simulates an exhaust (stream 44) gas cooling tower
Compr	C-AIRFAN	Used to model a cooler inlet air fan (stream 5)
	ID-FAN	Sucking out of exhaust gases (stream 14) from the kiln system
FSplit	FEEDSPLT	Splits stream 43 into two equal parts
FabFl	GASCLEAN	Cleaning of fine dust from gases (stream 18)

where q ($\text{kJ}\cdot\text{kg}^{-1}$) is specific heat energy consumption, HHV ($\text{kJ}\cdot\text{kg}^{-1}$) encompasses fuel higher heating values, \dot{m}_f ($\text{kg}\cdot\text{s}^{-1}$) is fuel flow rate, and \dot{m}_{cl} ($\text{kg}\cdot\text{s}^{-1}$) is clinker flow rate.

2.3. Validation of Simulation Results. Validation of the results started by comparing the weight percent composition of clinker, one obtained by simulation and the other obtained from chemical analysis of clinker that is produced in the MCC plant. The values of the weight percent composition that are presented in Table 2 could be generally rated to be in a good agreement, except in the case of some minor elements like sulphur trioxide (SO_3), potassium oxide (K_2O), and sodium oxide (Na_2O). The main reason for the observed disagreement between the calculated and real plant data could be the fact that some substances such as sodium sulphate (Na_2SO_4), potassium sulphate (K_2SO_4), calcium sulphate (CaSO_4), and tetracalcium aluminium ferrite (C_4AF) were not considered in the simulation model. Additionally, the

simulation model assumed that dicalcium silicate (C_2S) had completely reacted with free lime, calcium oxide (CaO), to form the tricalcium aluminate (C_3S).

Deeper analysis presented in [46] also indicates a relatively significant disagreement of the O_2 mass fraction in pre-heater exhaust gas between the calculated value and real plant data. The difference can be contributed to the unavoidable flow rate of in-leakages of air in the RKS, which was not accounted for in the simulation model. However, since the energy audit indicates 3.77% of the O_2 mass fraction in pre-heater exhaust gas, it became obvious that the useful thermal energy consumption in the plant was far from the optimum level. The high value of percentage oxygen also implied the increase of specific fuel consumption, which, in turn, would lead to more chemical irreversibility in the RKS and more CO_2 emission to the environment.

A second validation of the results, concerning the mass flow rate and temperature of some process streams, is

TABLE 2: Comparison of weight percent composition of clinker (in % wt) between the real plant data and simulation results.

Substance	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O
Real plant data	22.24	5.14	3.52	67.55	1.22	0.01	0.29	0.18
Simulation results	22.03	5.42	3.94	67.84	1.2	0.07	0.74	0.23
Substance	TiO ₂	MnO	CO ₂	H ₂ O	P ₂ O ₅	C ₃ S	C ₂ S	C ₃ A
Real plant data	0.3	—	—	0.02	0.04	70	30	10
Simulation results	0.07	—	—	—	0.03	71.89	32.45	11.02

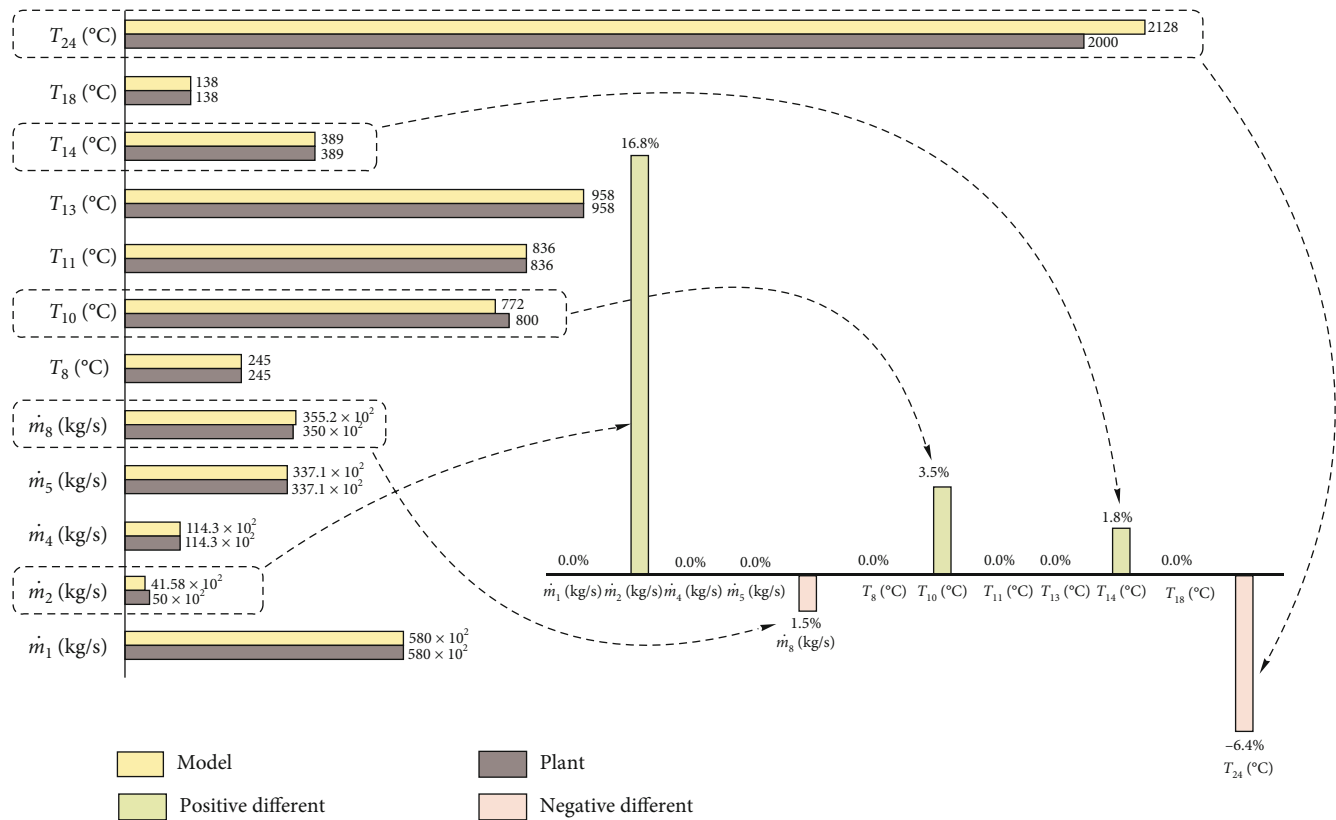


FIGURE 4: Validation of results obtained by simulation of RKS in Aspen Plus software.

illustrated in Figure 4. Like in the case above, most of the results obtained by simulation are in good agreement with the real operating data of the plant. However, there is a slight disagreement between the simulation results and real plant data in the case of coal, i.e., 5000 vs. 4158 in \dot{m}_2 (kg/s) and clinker, i.e., 35,000 vs. 35,528 in \dot{m}_8 (kg/s) mass flow rate. The reason for this could be the too high assumed values of cyclones and clinker burning efficiency in the simulation model. However, the simulation results indicated that the improvement of processes in cyclones, the rotary kiln, and the dust cleaning system can lead to the increase of material-use efficiency in RKS. Also, from the same figure, it can be observed that the temperature of secondary air, i.e., 800 vs. 772 in T_{10} (°C), obtained by simulation, deviated slightly from the real plant data, but was within the allowable range of secondary air temperature in similar plants. The deviation could be due to the type of process unit selected

in the simulation model, as well as due to the lower value of minimal available temperature differences used for the simulation of a heat exchanger. Another important parameter calculated by simulation, which deviates from the real plant data, is the temperature of combustion gases, i.e., 2000 vs. 2128 in T_{24} (°C). This deviation could be due to the fact that the model did not consider imperfections of the real plant.

3. Parametric Study Results of the Kiln System Using the Model

The parametric studies generate vital information for evaluation of cement kiln system production processes. Thus, the parametric analysis could be used to improve kiln system performance and evaluate environmental performance of the plant due to emissions arising from physiochemical reactions.

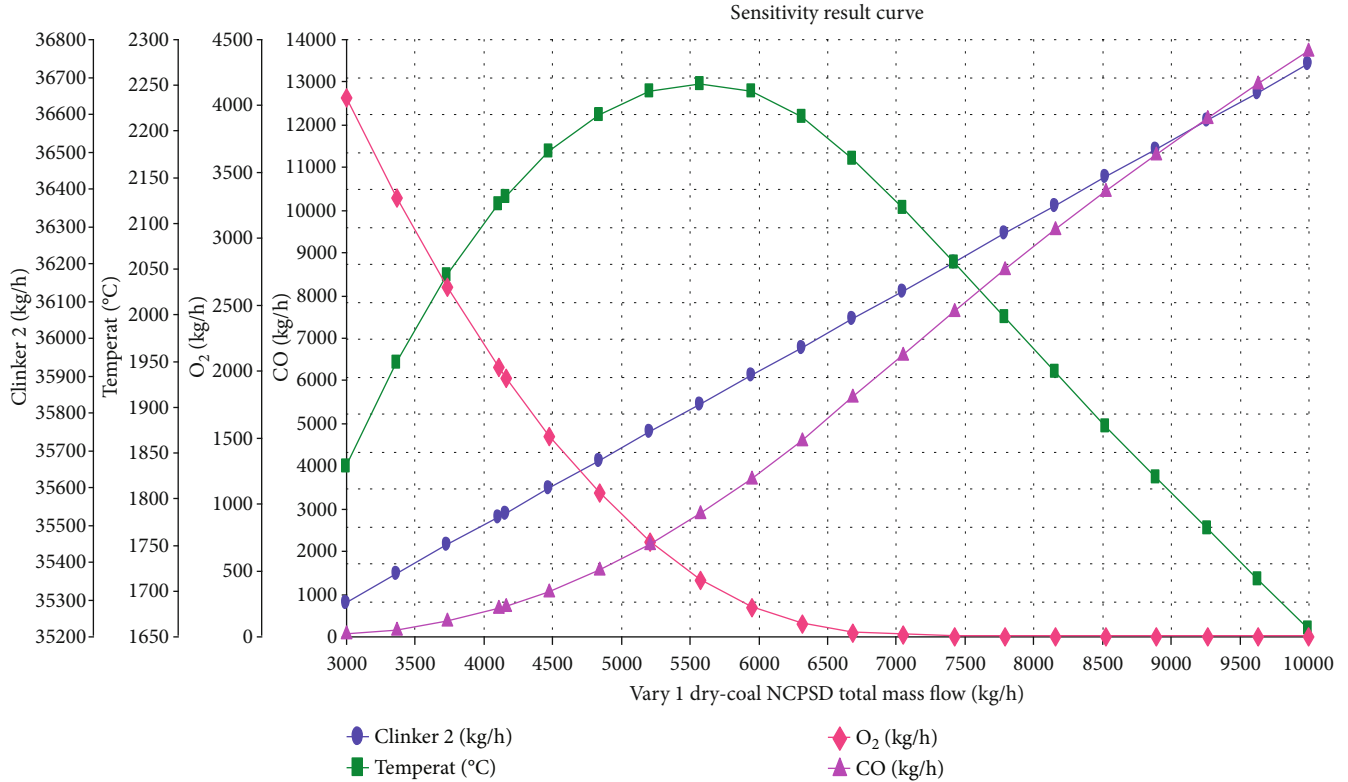


FIGURE 5: Coal flow rate vs. combustion efficiency and clinker production. Horizontal axis indicates coal flow rate and vertical axis indicates clinker, temperature, O₂, and CO values.

3.1. Combustion Temperature and Its Effect on Clinker Production. From the thermodynamics of combustion of rotary kiln systems' point of view, increasing coal flow rate raises burning temperature, as well as clinker production rate. However, increasing the fuel flow rate at stoichiometric conditions reduces the flame temperature [52]. In order to maintain the flame temperature, fuel and air flow rates are varied proportionately [1]. The results from Figure 5 suggest that the maximum temperature of $T_{\text{flame}} = 2250^{\circ}\text{C}$ is achieved at $\dot{m}_{\text{coal}} = 5580 \text{ kg} \cdot \text{h}^{-1}$. By increasing \dot{m}_{coal} beyond $5580 \text{ Ckg} \cdot \text{h}^{-1}$, flame temperature decreases to 1660°C at stoichiometric air.

Figure 5 also indicates that clinker production increases linearly with an increasing coal flow rate. This could be due to the temperature increase which accelerates calcination, as well as the contribution of ash content to the amount of clinker formed. It should be noted that the current operating coal flow rate at MCC is $\dot{m}_{\text{coal}} = 5000 \text{ kg} \cdot \text{h}^{-1}$, which gives a burning zone flame temperature of combustion gases of $T_{\text{flame}} = 2230^{\circ}\text{C}$. The result indicates that there is an opportunity for fuel saving. Suitable combustion gas temperatures for clinker burning found in the literature are from $T_{\text{flame}} = 1800^{\circ}\text{C}$ up to $T_{\text{flame}} = 2000^{\circ}\text{C}$ [51]. Figure 5 indicates that these temperatures can be achieved at $\dot{m}_{\text{coal}} = 3000 \text{ Ckg} \cdot \text{h}^{-1}$ ($T_{\text{flame}} = 1835^{\circ}\text{C}$) and $\dot{m}_{\text{coal}} = 3737 \text{ Ckg} \cdot \text{h}^{-1}$ ($T_{\text{flame}} = 2043^{\circ}\text{C}$), respectively. This could provide a minimum potential coal saving of about $\dot{m}_{\text{coal}} = 1263 \text{ kg} \cdot \text{h}^{-1}$,

which approximates to 76,126 tons per year at the current kiln feed of $58,000 \text{ kg} \cdot \text{h}^{-1}$. It should be pointed out that the current specific energy consumption of the kiln system is $4200 \text{ kJ} \cdot \text{kg}_{\text{cl}}^{-1}$ at a clinker throughput of $\dot{m}_{\text{CLINKER}} = 35,000 \text{ kg} \cdot \text{h}^{-1}$. Therefore, the coal input of $\dot{m}_{\text{coal}} = 3737 \text{ kg} \cdot \text{h}^{-1}$ to the kiln is equivalent to the specific useful energy consumption of $2350.88 \text{ kJ} \cdot \text{kg}_{\text{cl}}^{-1}$, which gives a clinker output of $\dot{m}_{\text{CLINKER}} = 35,441.5 \text{ kg} \cdot \text{h}^{-1}$. Thus, this translates to a specific energy saving of about $1849.12 \text{ kJ} \cdot \text{kg}_{\text{cl}}^{-1}$, with a relatively higher clinker throughput. Note that the specific useful energy consumption was calculated using equation (2). However, such fuel saving is only possible if the plant runs without any heat losses.

Moreover, Figure 5 indicates that increasing the coal flow rate above an optimum value will lower combustion efficiency, which is indicated by an increase in carbon monoxide (CO). This is explained by the fact that increasing the coal flow rate at a constant supply of combustion air results into a dramatic decrease in O₂ as indicated in the same figure. The decreases in O₂, in turn, result into the incomplete combustion of coal.

3.2. Variation of Primary Air and Its Impact on Clinker Production. Traditionally, rotary kiln burning operation control is done by the adjustment of the raw feed, fuel flow rate, and ID fan speed. However, oxygen target level is very

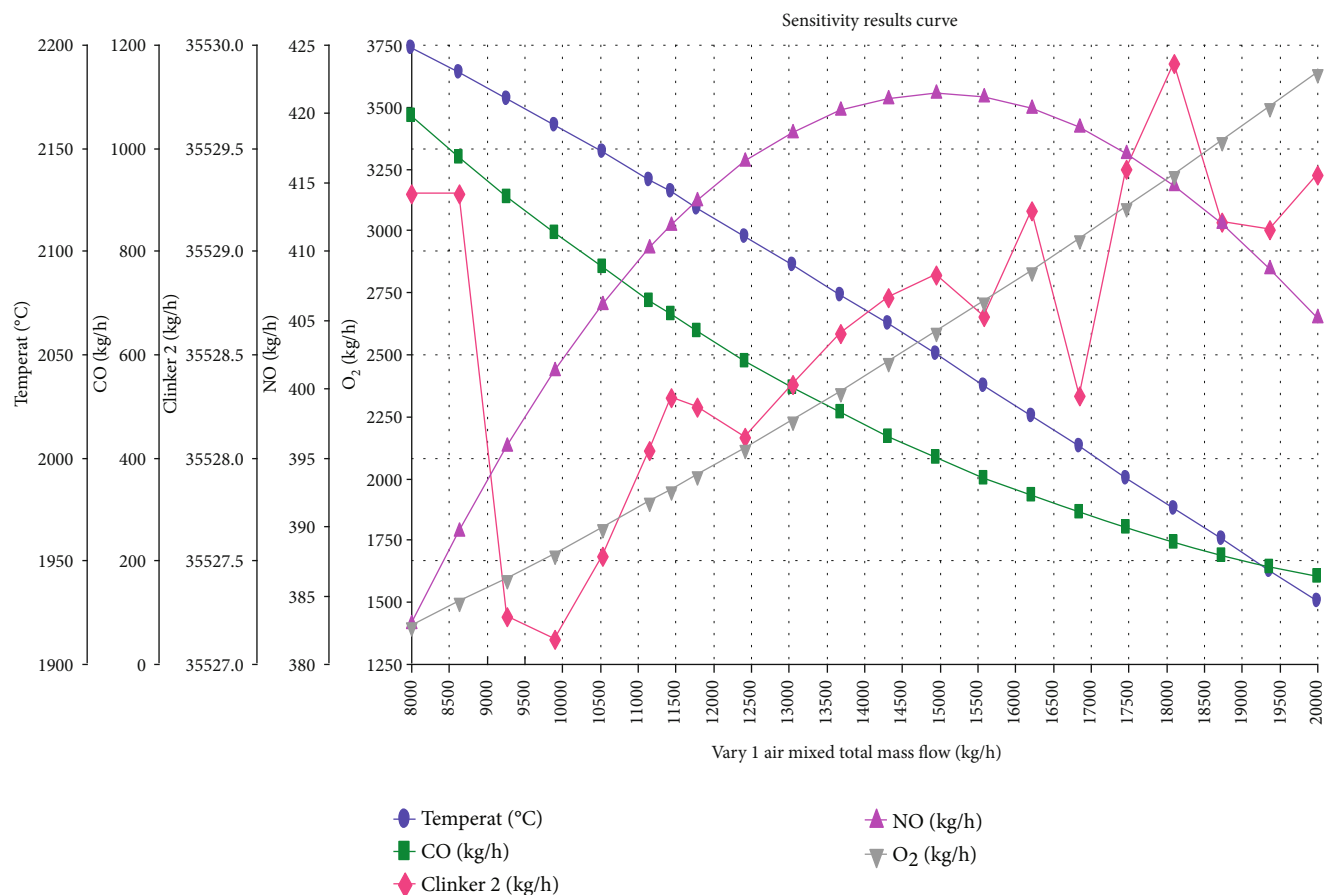


FIGURE 6: Primary air flow rate (horizontal axis) vs. clinker production, O₂, NO, CO, and flame temperature (vertical axis).

important not only for the complete combustion of fuel, but also for better clinker burning conditions.

The right amount of oxygen for complete combustion is very important for the thermal performance of a rotary kiln. However, an exceeding oxygen level indicates more combustion air into the system than expected. This will result into a significant amount of useful energy from the combustion of fuel being used for heating up of excess air, thereby cooling down the burning zone temperature as indicated in Figure 6. The latter will result into kiln system heat losses. In other words, it can be stated that the higher the percentage of excess air, the greater the exergy destroyed by the thermal exergy of combustion gases. Figure 6 indicates that varying primary air beyond 15,000 kg·h⁻¹ clinker production is unstable or varies irregularly. It is also indicated that NO emission increases, but when primary air is beyond $\dot{m}_{\text{air}} = 15,000 \text{ kg} \cdot \text{h}^{-1}$, emission starts to decrease. The increase in NO emission below $\dot{m}_{\text{air}} = 15,000 \text{ kg} \cdot \text{h}^{-1}$ primary air flow rate is due to the increased amount of N₂ contained in primary air at elevated temperature, but above $\dot{m}_{\text{air}} = 15,000 \text{ kg} \cdot \text{h}^{-1}$ the combustion temperature is cooled down by excess air volume at lower temperature. The NO_x level in the outgoing gases gives information about combustion processes. It should be pointed out that a high peak temperature in the combustion zone leads to a higher NO_x level, among other things. Thus, for any given

type of kiln, the amount of NO_x formed is directly related to the amount of useful energy consumed in the clinker burning process. Therefore, measures that improve the energy efficiency of this process should reduce NO_x emissions as well.

It should also be noted from Figure 6 that CO decreases with an increase in the primary air flow rate, indicating that complete combustion is approached with excess air. It should be noted further that increasing excess air at a certain point may improve combustion efficiency, but when it exceeds the acceptable value between 1% and 2% O₂ (10%-15% excess air), combustion efficiency is lowered followed by unstable kiln operation indicated by irregular clinker production in Figure 6. Furthermore, it can be noted that O₂ increases with primary air increase. Exceeding the primary air above $\dot{m}_{\text{air}} = 20,000 \text{ kg} \cdot \text{h}^{-1}$ brings errors to the simulation, and the simulation fails to converge, probably due to an excessive air flow rate, which contributes to an excessive mass flow rate above optimal values allowed to some components such as cyclones, thereby, causing excessive pressure drops and blocking cyclone outlets, due to overloading. An excessive air mass flow rate may also cause problems to reactors due to excessive cooling.

3.3. Variation of Cooling Air and Its Effect on Energy Use. In a rotary kiln system, it is very important to keep the secondary combustion air temperature at a constant acceptable level of

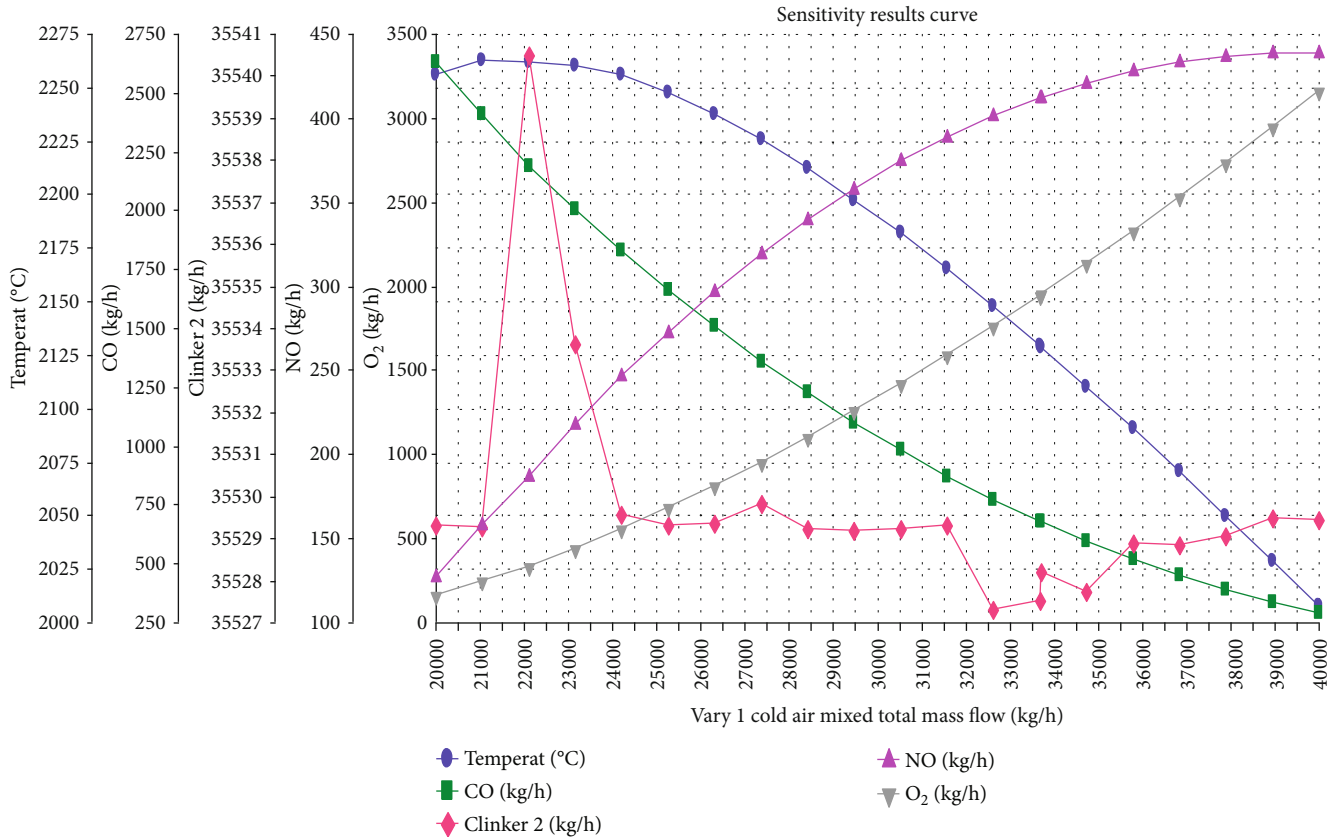


FIGURE 7: Cooling air vs. clinker production and combustion emissions.

between $T_{\text{flame}} = 800^{\circ}\text{C}$ and 1000°C [1]. This is very important for the stable and smooth operation of the kiln. Furthermore, the efficiency of the clinker cooler and the kiln system, at large, is mainly constrained by heat recovered from a hot clinker by secondary air. Therefore, results from Figure 7 suggest that an excessive increase in cooling air flow rate lowers the combustion temperature. Increasing the cooling air flow rate above the optimal value causes an unstable kiln operation. That is, varying the cooling air flow rate causes a fluctuating secondary air temperature, thereby causing the cycling of the kiln operation. The latter results into irregular clinker production as indicated in Figure 7. This phenomenon is also supported by the findings of [39, 53]. In Reference [39], it was observed that too large an amount of secondary air fed to the burning zone interrupted clinker formation, where the flame becomes unstable, the burning zone is cooled, and a lot of dust is in circulation in the kiln and precalciner system. Furthermore, the findings of [39] indicate that a variation of secondary combustion air changes the formation of clinker minerals, whereby alite content goes down and the belite content grows rapidly. These changes are usually caused by the increase of oxygen. Arad et al. [53] pointed out that a nonuniform clinker product output suggests that large temperature gradients exist near and within the rotary kiln bed. Generally, the demand of combustion air in the burning zone appears to have a large influence on the results.

Furthermore, increasing the cooling air volume above an optimal value lowers combustion gas temperatures, thereby lowering kiln thermal efficiency (Figure 7). It can also be noted from Figure 7 that increasing the cooling air flow rate will lower CO emission, while increasing NO emission and O₂ flow rate.

3.4. Coal Variation and Its Effect on Combustion Emissions. Coal flow rate was varied in order to study the contribution of coal burning to environmental pollutions. It can be noted from Figure 8 that CO increases exponentially with the coal flow rate. It is also noted that CO₂ increases with a coal flow rate up to $\dot{m}_{\text{coal}} = 4800 \text{ kg} \cdot \text{h}^{-1}$ when it starts to decline with an increasing coal flow rate. Such decrease in CO₂ can be explained by the fact that a further increase in the coal flow rate will increase flame temperature, which, in turn, results into CO₂ dissociation to form CO.

Furthermore, Figure 8 indicates that NO₂ increases with a decreasing coal flow rate, while NO increases up to a coal flow rate of $\dot{m}_{\text{coal}} = 4000 \text{ kg} \cdot \text{h}^{-1}$, from where it starts to decline. The decrease in NO with an increasing coal flow rate beyond $\dot{m}_{\text{coal}} = 4000 \text{ kg} \cdot \text{h}^{-1}$ could be due to a decrease in O₂ with an increasing coal flow rate as predicted in the same figure. Normally, it is expected that thermal NO_x emission should increase at elevated temperatures, although that depends on the availability of oxygen and nitrogen from excess air.

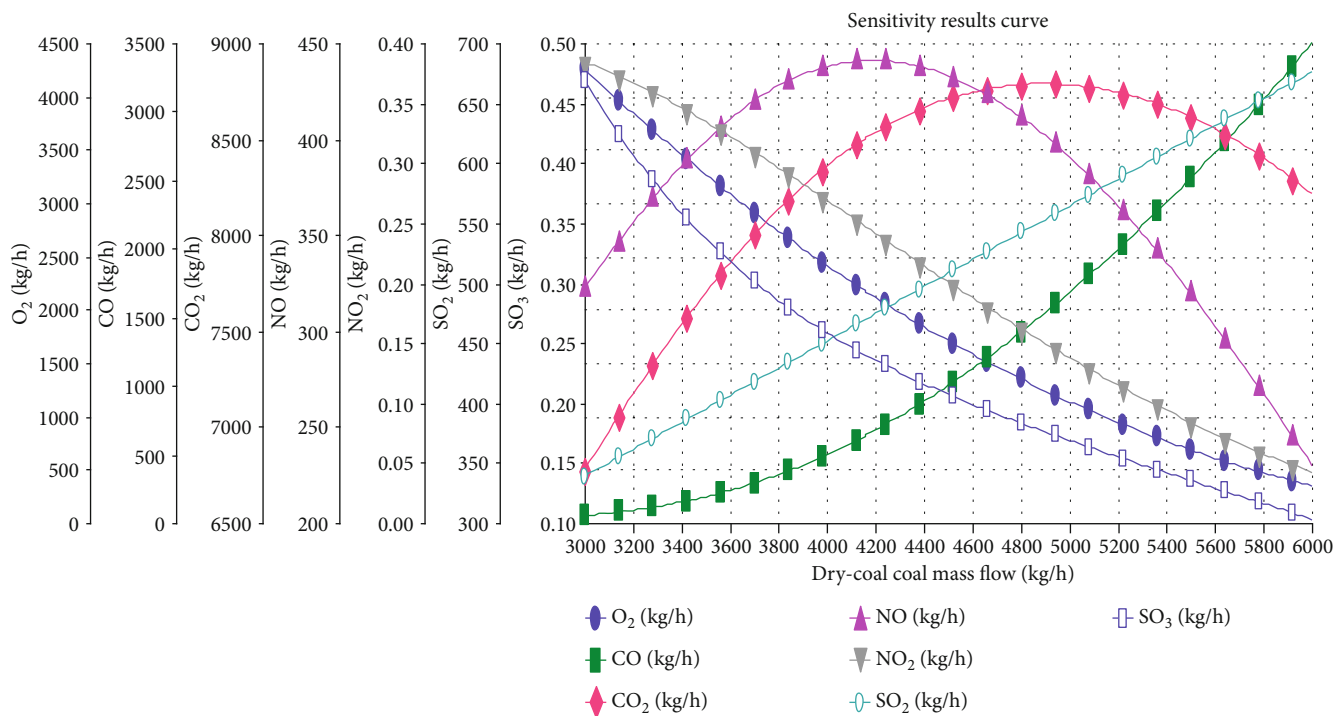


FIGURE 8: Coal flow rate vs. combustion gases composition.

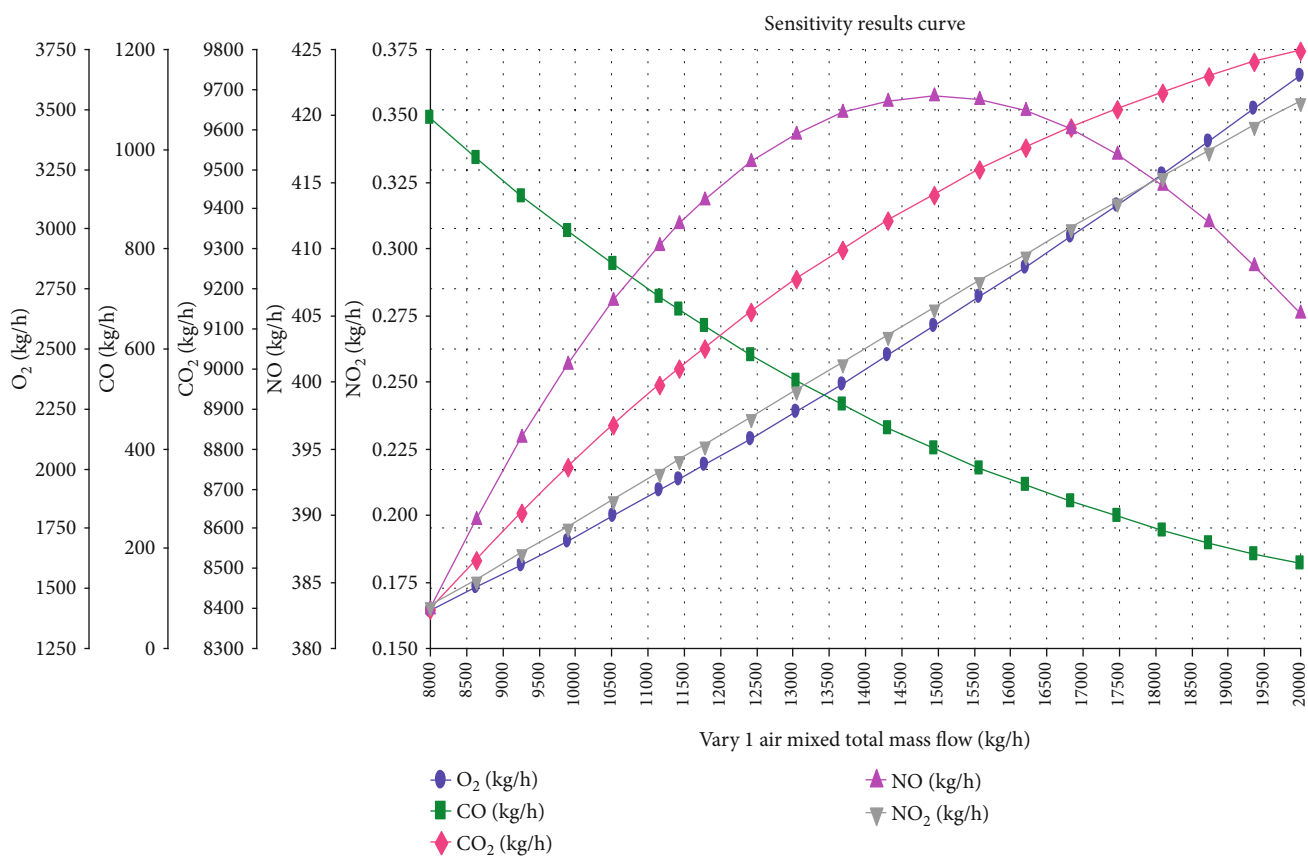


FIGURE 9: Primary air vs. combustion gas composition.

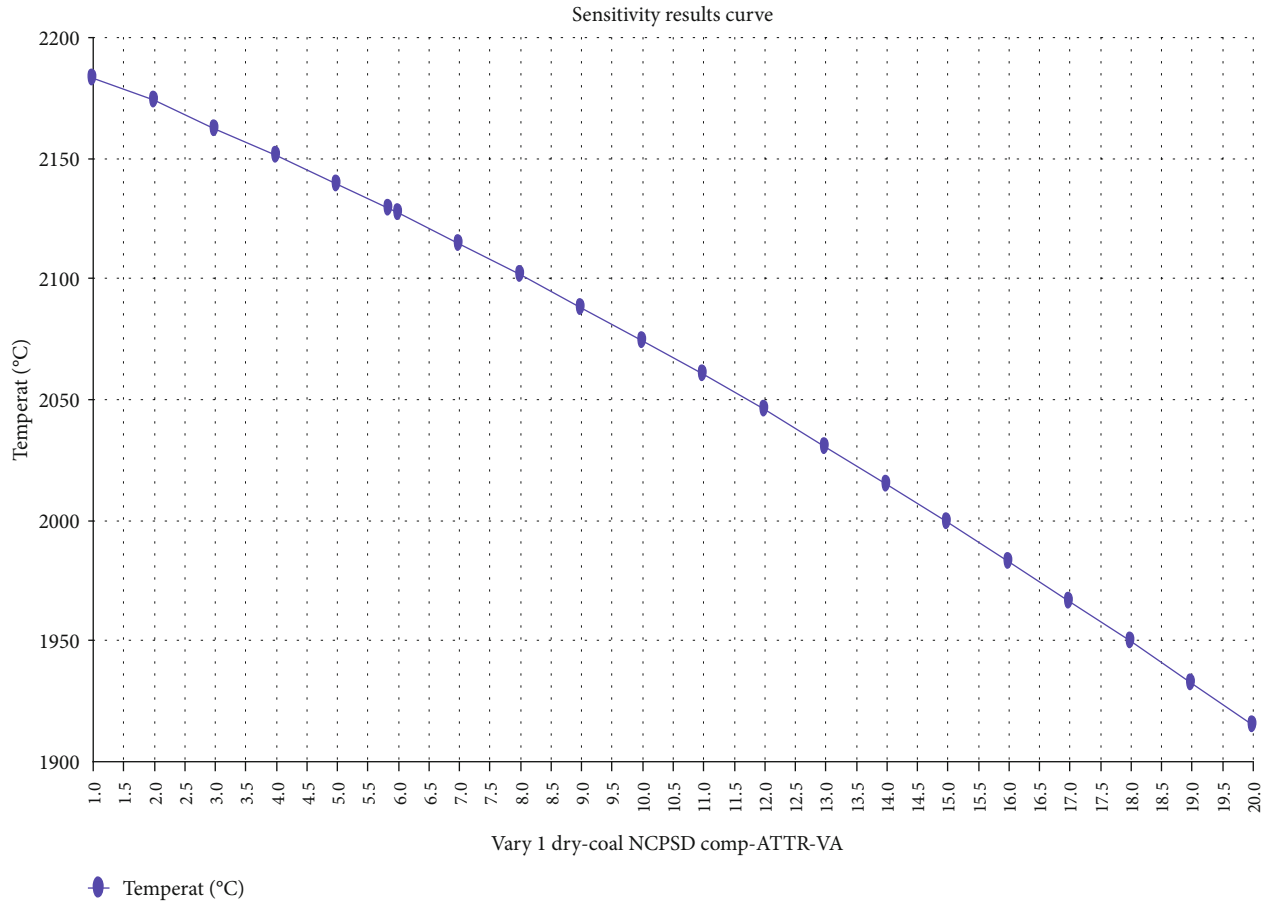


FIGURE 10: Coal moisture content vs. combustion temperature.

3.5. Variation of Primary Air and Its Effect on Combustion Emissions. The findings in Figure 9 reveal that CO decreases with an increasing primary air flow rate. The decrease in CO could be a result of more oxygen supply, which, in turn, facilitates complete combustion. It should be pointed out that the presence of CO near the main flame has a negative influence on clinker quality. NO increases with the air flow rate up to the primary air flow rate of $\dot{m}_{\text{air}} = 15000 \text{ kg} \cdot \text{h}^{-1}$ and starts to decrease with an air flow rate increase. It is important to mention that NO in cement kilns has correlation to free-lime content in clinker and, hence, is used to determine clinker quality. The figure further predicts that NO_2 increases linearly with the primary air flow rate, while O_2 increases with the increasing primary air flow rate. It is also observed that CO_2 increases exponentially with the primary air flow rate.

3.6. Effect of Coal Moisture Content on Combustion Temperature. It is observed from Figure 10 that increasing the moisture content of coal can result into a lower combustion flame temperature.

The raw coal at MCC has a moisture content of 8%. Thus, it can be observed from Figure 10 that at the coal moisture content of 8% the combustion flame temperature of combustion gases is lowered to $T_{\text{flame}} = 2100^\circ\text{C}$. Therefore, it can be concluded that burning coal with a higher moisture

content in a rotary kiln will affect the thermal efficiency of the kiln.

4. Conclusion and Future Work

In general, results obtained from the parametric studies of the model give important insights into the possibilities available for the improvements of specific energy use and emissions in the cement dry rotary kiln system. Additionally, parametric studies generate vital information for the evaluation of cement kiln system production processes. Thus, the parametric analysis could be used to improve kiln system performance and evaluate the environmental performance of the plant caused by emissions. Parametric analysis studies uncovered the following:

- (i) Monitoring of flue gases for O_2 and combustibles allows the process to be operated more safely and efficiently
- (ii) Maintaining the air/fuel ratio within a specific range is very important for the performance of the kiln system, including the quality of clinker produced
- (iii) Monitoring CO and combustibles could prevent build-ups to levels that can cause an explosion in the ESP, bag house, as well as ID fans

- (iv) Significant reduction in emissions of NO_x , together with other pollutants, could be achieved by maintaining good combustion control
- (v) Reliable flue gas analysis could provide information for the effective control of the kiln system

Predictions from parametric studies suggest that monitoring and regulating exhaust gases could improve combustion efficiency, which, in turn, could lead to conserving fuels and lowering production costs. Complete combustion will occur when proper amounts of fuel and air (fuel/air ratios) are mixed for correct amounts of time under appropriate conditions of turbulence, as well as temperature. The amount of fuel supplied to the system depends on its calorific value, which means, the higher the calorific value, the lesser the amount of fuel required, and vice versa. The composition of exhaust gases also depends on the type of fuel used and amount of combustion air. The volume and temperature of exit flue gases from a pre-heater cyclone could also affect fuel consumption in the kiln system. The volume of exit flue gases depends on the amount of combustion air and infiltrating air in the kiln system.

Results obtained from parametric analysis suggest that the maximum fuel flow rate possible at the MCC kiln burner is $\dot{m}_{\text{coal}} = 5580 \text{ kg} \cdot \text{h}^{-1}$ (current $\dot{m}_{\text{coal}} = 5000 \text{ kg} \cdot \text{h}^{-1}$). Increasing the coal flow rate above $\dot{m}_{\text{coal}} = 5580 \text{ kg} \cdot \text{h}^{-1}$ could lower the thermal efficiency of the kiln system. The current coal flow rate of $\dot{m}_{\text{coal}} = 5000 \text{ kg} \cdot \text{h}^{-1}$ gives a simulated burning zone gas temperature at $T_{\text{flame}} = 2230^\circ\text{C}$, which is above the typical plant temperature between $T_{\text{flame}} = 1800^\circ\text{C}$ and $T_{\text{flame}} = 2000^\circ\text{C}$, suggesting for an opportunity of fuel saving or more clinker production.

It was observed from the parametric analysis that the higher the excess air for combustion above optimal values, the greater the exergy destroyed due to the thermal cooling of the exergy of combustion gases. Generally, the demand of combustion air in the burning zone appears to have a large influence on the results.

In the future, further parametric studies to explore physical parameters such as specific kiln volume loading, flame height, ID fan speed, and particle size within the rotary kiln bed using Aspen Plus, together with CFD software could be considered. Furthermore, a heat recovery feasibility study could be performed based on the exhaust gas condition predictions made under this study.

Data Availability

Data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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