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ORIGINAL PAPER

Aspen Plus-based simulation of a cement calciner and optimization analysis of air pollutants emission

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Abstract The cement industry is a typical high energy consumption and heavy pollution industry, in which amounts of CO_2, NO, NO_2, and SO_2 discharge from the pre-calciner kiln system and cause severe greenhouse and acid rain effects. Meanwhile, reasonable division of the combustion environment in the calciner is the main method to control the formation of pollutant gases. In this article, a calciner process model in Aspen Plus is proposed based on the combustion mechanism analysis of the Dual Combustion and Denitration calciner (DD-calciner) and verified by industrial data. Then, for a concrete DD-calciner, the article studies the effects of the flow rate of coal and tertiary air on flue gas compositions and effects of the staging combustion technology on the NO_x, SO_2, and CO concentrations in the flue gas. Through comparing the model results with the relevant environmental standards, the optimization analysis for staging combustion parameters of the calciner is done, and the result shows that when the proportion of tertiary air entering the pyrolysis and combustion zone is controlled within the range of 57–65.52% ($0.89 < \alpha < 1.004$), all the gas pollutants emit within accepted standards simultaneously. The calciner process model outlined in this article describes the key processes of the physical and chemical reactions in the calciner. It can be used to study the key operation and design parameters which influence the flue gas constituents, so as to provide data support for determining the pollutant emission reduction plan of the cement industries with a view to reduce air pollutant emission.

Keywords Calciner · Mechanism analysis · Aspen Plus · Staging combustion · Emission reduction

Introduction

The cement industry is a typical high resource consumption, high energy consumption, and heavy pollution industry, whose fast development simultaneously causes severe resource, energy, and environmental problems. The new dry process cement production technology, which is also known as pre-calcining technology reduces heat loads and gas pollutants formation in the rotary kiln system because this method makes it possible to transfer the heavy raw material decomposition tasks to outside the kiln. Facing the continuous increase in the need for cement and much stricter environmental standards for the cement industry, the pre-calcining technology has been widely adopted to replace some of the backward production processes like the shaft kiln process. The calciner is one of the key pieces of equipment in pre-calcining process, and mainly undertakes the tasks of partial fuel combustion, gas–solid heat exchanges and much of the raw material decomposition. The extent of fuel combustion and raw material decomposition have a direct relationship to aspects such as the clinker quality, energy consumption, and pollutants emission, so studying the control and optimization of the calciner parameters is a focal issue that has received much attention currently in the field of cement technology.

On the whole, recent studies of the cement calciner have mainly focused on the numerical modeling domain based

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on computational fluid dynamics (CFDs). This emphasizes the study of the kinetic behavior of fluids and the kinetic process of fuel combustion and raw material decomposition in the calciner, with less attention to gas pollutants formation during the entire process (Kääntee et al. 2003). The air pollutants of the cement industry mainly discharge from the calcination process in the calciner and rotary kiln. As the calciner undertakes the major tasks of fuel combustion and raw material decomposition, pollutants such as CO_x, NO_x, and SO_x will be produced (Mujumdar et al. 2007). For the syntenic calciner, the flue gas from the kiln inlet carrying a relatively high concentration of thermal NO_x enters the calciner and participates in the physical and chemical processes in the calciner, which influences the gas constituents. Therefore, the study of gases formation in the calciner plays an important role in reducing the environmental impact on the air by cement industries. Furthermore, the cement industry is a typical process industry, so it is more direct in evaluating the performance of the calciner as a whole to study the calcination processes of the calciner unit from a process industry system perspective (Kääntee et al. 2002). As a steady-state process simulation software package, Aspen Plus is universally used in process industry systems and possesses powerful property databases of a variety of physical parameters including inorganic, organic, solid and combustion products, convenient and flexible unit operation modules, and a user-friendly graphical interface (Zhao 2003; Aspen Plus Version 10.2 User Manuals, 2000). After establishing an accurate steady-state model via analysis of the actual situation, Aspen Plus calculates the unit and entire process balance using strict and scientific methods based on the material and energy conservation principles of the system. This can be used to analyze the existing techniques and facilities for parameter optimization and to optimize the design of a new program. At present, Aspen Plus has been widely used in the simulation of iron manufacture, metallurgical process, Al_2O_3 production, coal and biomass gasification and combustion, solid waste combustion, and gas pollutants capturing processes, etc. In particular, it has been used in the modeling of combustion processes, providing a more mature approach (Schultmann et al. 2003; Zheng and Furimsky 2002; Chuen 2000; Zhang et al. 2003; Lucas et al. 2007; Fan et al. 2008; Wang and Anthony 2007; Zhou 2008; Zhang et al. 2008a, b; Cimini et al. 2004; Dai et al. 2008).

Based on the function analysis of Aspen Plus and mechanism analysis of the calciner, this article proposes a new method to simulate gas formation in the calciner and to optimize the calciner parameters. The calciner simplified process model is built up using Aspen Plus via assumptions of partial processes in the calciner, and verified by industrial values. The model is then applied to the actual cement industry to analyze the effects of staging combustion technology usually used in the calciner, on the flue gas constituents. Finally, a staging combustion plan is created which can ensure all the gas pollutants are emitted within accepted standards. Figure 1 shows the specific research flow path of this article. The calciner process model outlined in this article describes the key processes of the physical and chemical reactions in the calciner. It can be used to study the key operation and design parameters which influence the flue gas constituents, so as to provide data support for determining the pollutant emission reduction plan of the cement industries with a view to reduce air pollutant emissions.

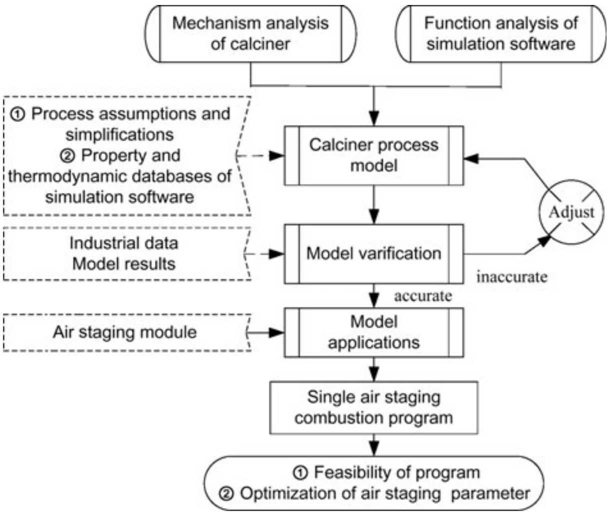

Fig. 1 Research flow path of this article

Principles of the calcination process

There are two main types of reaction in calciner: coal combustion reactions and carbonate decomposition reactions. The pulverized coal and raw materials are mixed and suspended in the thermal current, where exothermic combustion reactions and endothermic calcination reactions take place and which keep the temperature of the calciner slightly higher than the equilibrium temperature of carbonate decomposition (Mujumdar et al. 2007). This article builds up a calciner unit model based on the 2500t/d DD-calciner prototype. According to characteristics of coal combustion, the 2500t/d DD-calciner can be divided into three sections which consist of the fuel pyrolysis and combustion zone, main combustion zone, and complete combustion zone, with the endothermic calcination reactions of raw material happening in each section (Fidaros et al. 2006; Huang 2006). Figure 2 shows the internal partitions of a DD-calciner.

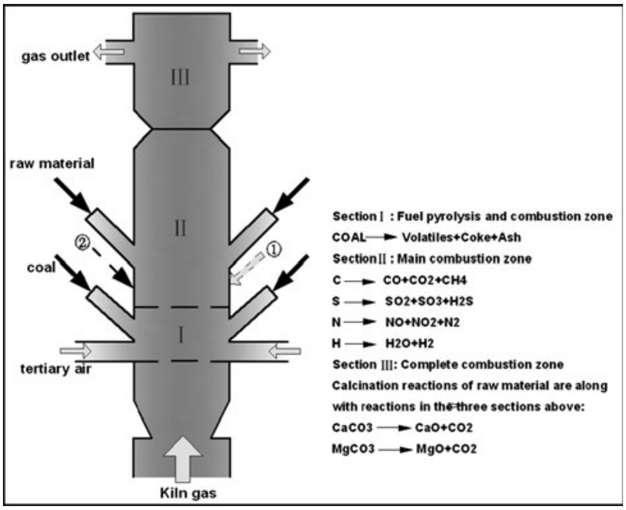

Fig. 2 Internal partitions of a DD-calciner (Li 2006)

Fuel pyrolysis and combustion zone (Section I): after being injected into the furnace, the pulverized coal cracks rapidly in the tertiary air and flue gas from the kiln inlet with high temperature and abundant oxygen, which results in the release of volatiles and generation of coke. Then the volatiles combust rapidly and transfer the heat of combustion to the raw materials for decomposition.

Main combustion zone (Section II): a large quantity of volatiles and coke combust and supply large amounts of heat to the raw material. The raw material decomposes rapidly by absorbing the heat of combustion, which keeps the temperature of the calciner distributed evenly over a relatively low range (850–900°C).

Complete combustion zone (Section III): a small portion of unburnt fuel continues to burn to promote further decomposition of the raw material.

Calciner-simplified model

Combining the principles of the cement calciner process and the features of the Aspen Plus simulation software, this section proposes several assumptions for simplifying the calciner, builds up the calciner process model based on Aspen Plus, and verifies the accuracy of the model using industrial data.

Process assumptions

The cement calciner is a typical gas–solid two-phase flow reactor, where not only the physical and chemical reactions of the gas–solid phase take place, but also complex fluid motion and heat transfer effects of gases and solids are in progress at the same time, which have an influence on the extent of the chemical reactions in the calciner. Since the aim of building the calciner model is to study the interrelationship between input materials and output materials, and between input energy and output energy, the following five assumptions of the calcination process are adopted during modeling.

(1) In the calciner, the coal combustion and the raw material decomposition processes take place in two different reactors. The coupling effect between the performances of the two types of reactions reflects in the temperature, which is controlled by setting the temperature of combustion in the model. The combustion process consists of the coal pyrolysis section and pyrolysis products combustion section, which are simulated using two reactor modules.

(2) All the NO_x produced in the whole process are fuel NO_x, formed from the conversion of nitrogen in the fuel, and the nitrogen in the air is nonreactive.

(3) The ratio of the volatile-N to coke-N in the fuel is 1:1 (Friebel and Kopsel 1999), because the transformation pathways are different for the nitrogen in different existence states. According to the transformation pathways, all the volatile-N is represented by NH_3, which burns completely, and coke-N is treated as N_2 for which the release rate of N is approximately equal to the burning rate of coke (Tsubouchi and Ohtsuka 2008; Song et al. 2009). The unburnt coke-N in the fuel is treated as inert matter together with the nitrogen in the air.

(4) The degree of coal combustion is another consideration defined by the burn-off rate of coke, and the unburnt carbon is treated as an unconventional component named UBC (Zhang et al. 2008a, b). ASH is treated as inert in the combustion process, which does not participate in combustion reactions.

(5) Only the decomposition of the carbonate in the raw material is taken into account, and oxides like SiO_2, Fe_2O_3, and Al_2O_3 are treated as inert. Similarly, some trace reaction products such as COS, CS_2, N_2O etc. are not considered.

(6) The calciner is in a steady-state operating condition which ignores pressure losses, turbulent motions, and air leakages in the system. All the reactions in each section take place at the same temperature and can achieve equilibrium.

Calciner process model

Figure 3 shows the calciner process model in Aspen Plus built according to the simplified reaction processes in the calciner. The model includes 5 unit operation modules, 2 Fortran modules, 2 design specification modules, and 15 streams. In the model, coal is processed using the

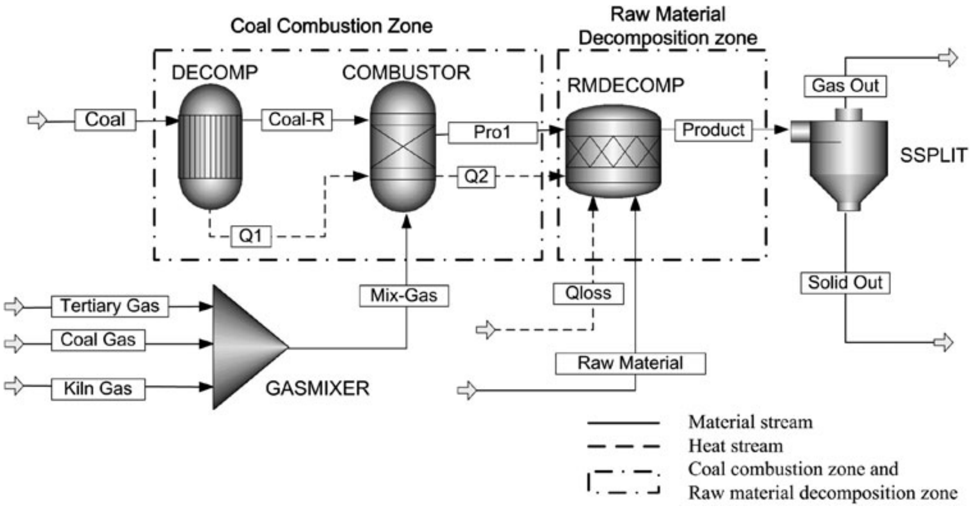

Fig. 3 Calciner process model in Aspen Plus

traditional approach in Aspen Plus, which means that initially, coal pyrolyzes into conventional components (C, CH_4, H_2, O_2, N_2, NH_3, S, Cl_2, and ASH) in the RYIELD reactor module (DECOMP) according to the proximate and elemental analyses of coal. Then the combustion process of coal is simulated using the RGIBBS reactor module (COMBUSTOR) which calculates the equilibrium compositions of products with the Gibbs free energy minimum method (Hoffman 2003; Koukkari and Pajarre 2006; Li 2002). The decomposition process of raw materials in the calciner is simulated with the RSTOIC reactor module (RMDECOMP) (Hughes et al. 2004), in which only the decomposition reactions of carbonates take place and oxides in the raw material like SiO_2, Fe_2O_3, and Al_2O_3 are treated as inert. In this model, two design specifications are set up to control the temperature of each block and the amounts of exit gases, by varying the flow rate of the relevant feed streams. The PENG-ROB method is used as the global property method to compute the thermodynamic properties of every stream. The operation conditions and temperature of combustion are determined by the actual industrial situation.

For the calciner process model above, Aspen Plus calculates the material and energy balance of every unit operation block in the order specified by the user, after setting the operating parameters of each block and the state parameters of individual material and heat streams. The model can be used to simulate the actual industries after verifying its accuracy by comparing the calculated results of the model with the industrial data. The specific implementation procedure of the model is shown in Fig. 4.

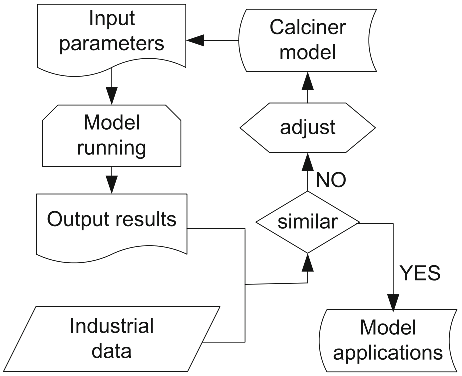

Fig. 4 Implementation procedure of the model

The input parameters in the model include:

(1) The temperatures, pressures, and flow rates of the incoming streams including fuel, raw material, tertiary air, air carrying coal, and flue gas from the kiln inlet;

(2) The proximate analysis, elemental analysis, heat value on a dry basis and particle size distributions of coal, composition analysis of flue gas from the kiln inlet, and chemical compositions of the raw material with particle size distributions;

(3) The outlet pressure of the calciner and temperature of coal combustion.

The output parameters in the model include:

(1) Flow rates and fractions of all the product components in the exit gases including CO, CO_2, NO, NO_2, SO_2, SO_3, O_2, N_2, H_2O etc., and the total flow rate of the exit gas.

(2) The flow rate, temperature, enthalpy, entropy, density, and average molecular weight of each stream;

(3) The content of $CaCO_3$, CaO, MgO, $MgCO_3$, and other oxides in the solid-phase sub-stream.

(4) The output temperature, pressure and heat duty of each reactor, and the state of material and energy balance in the reactors etc.

Simulated results and model verification

In this article, the actual operating parameters of the 2500t/d DD-calciner (Ex.1), 2000t/d DD-calciner (Ex.2), and the calciner with swirl and suspension effect (Ex.3) in the literature (Huang 2006) are selected as the input parameters to run the calciner process model in Fig. 3. The comparisons between simulated results and measured results shown in the literature (Huang 2006) are listed in Table 1. The model of the calciner with swirl and suspension effect is a little different from the original model in the simulation.

Comparison of results shows that the calciner process model is able to predict the outlet temperature and contents of flue gas components with a high level of agreement with the values in the literature. The generation of pollution gases in the pre-calciner kiln system and the controlling of the calciner temperature can be controlled efficaciously by adjusting the input parameters of the incoming streams and parameters of the relevant blocks of the model, which greatly reduces the cost and complexity of regulating and controlling the calciner using experimental methods. The results of the calciner process model can be used as a theoretical basis for reducing emission of air pollutants and help determine the pollutant emission reduction program in cement industries. Factors affecting the component and content of flue gas will be analyzed in the following sections using the simplified model of the calciner described in this section, thereby providing data to support the optimizing of the input stream parameters of the calciner.

Analysis of factors affecting the flue gas composition in the calciner

There are many factors that influence components of the flue gas, including the physical and chemical properties of fuels and raw materials, operating conditions, flow rates of incoming streams such as coal stream, raw material stream and tertiary air stream, temperature of tertiary air, and flue gas from the kiln inlet etc. Of these, changes in the flow rates of coal, raw material, and tertiary air stream have the strongest influence on the flue gas composition (Mujumdar and Ranade 2006). The flow rate of raw materials in the calciner is regarded as an uncontrolled parameter and is not considered, because it depends on the flow rate of raw materials in the suspension pre-heaters. In addition, to ensure that the pulverized coal combusts completely, the outlet temperature of the calciner must be kept in the range of 850–950°C (Fidaros et al. 2006) to prevent further combustion of the excess coal in the last cyclone. Therefore, the effects on the temperature when model parameters change should also be considered. This article takes the 2500t/d DD-calciner (Ex.1), for example, and models the effects of the flow rate of coal and tertiary air on flue gas compositions using the calciner process model built in Fig. 3. The excess air factor (α) reflects the influence of the tertiary air, which ranges between 1.05 and 1.25. The flow rate of coal ranges from 1500 to 15000 kg/h.

Figures 5, 6, 7, and 8 show changes in concentration of NO, CO, CO_2, and SO_2 in the flue gas due to variations of the flow rate of coal and excess air factor (α) with small changes in the flow rate of raw materials and the temperature of the tertiary air.

It is obvious that increasing the flow rate of coal without changing the excess air factor of the calciner causes large rises in the concentration of NO, CO, and SO_2 in the flue gas, because these three gases are mostly formed from the chemical changes of the N, C, and S elements in coal. Whereas, keeping the flow rate of coal in the calciner constant, and increasing the amounts of air entering the calciner, causes a rapid decline in the concentration of the reductive NO, CO, and SO_2. Furthermore, the concentration of CO_2 in the flue gas decreases with increase in the flow rate of coal and tertiary air, but simultaneously does

Table 1 Comparisons between simulated results and literature values

Input				Output						
Material streams (kg/s)	Literature data (Huang 2006)			Compared objects	Ex.1		Ex.2		Ex.3	
	Ex.1	Ex.2	Ex.3		Liter-value	Simu-result	Liter-value	Simu-result	Liter-value	Simu-result
Raw material	44.69	48.84	56.24	Outlet-*T*(K)	1176	1175	1163	1193	1154	1194
Coal	2.1	2.12	3.13	NO (mg/Nm^3)	776	774.68	–	765.3	–	498
Tertiary air	21.94	23.87	24.38	O_2 (%)	2.282	2.47	1.35	1.14	1.46	1.65
Flue gas from the kiln inlet	15.34	14.84	19.56	CO (%)	0	1.54 E−8	–	2.43 E−8	–	1.63 E−8
				CO_2 (%)	–	39	36.6	40.3	40.12	38.9

– Means data is not found in the literature, *Outlet-T* represents the outlet temperature of calciner, *NO* represents the average concentration of NO in outlet flue gas, O_2, CO, and CO_2 represent the mass fraction of O_2, CO, and CO_2 in the outlet flue gas

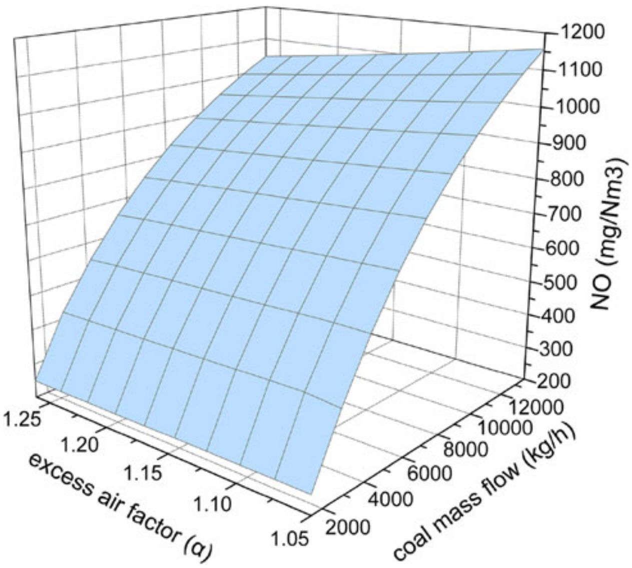

Fig. 5 Effects of the flow rate of coal and excess air factor on NO in flue gas

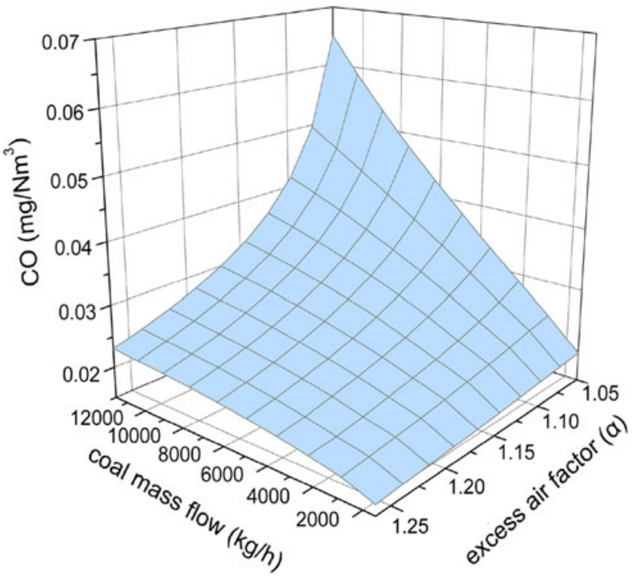

Fig. 6 Effects of the flow rate of coal and excess air factor on CO in flue gas

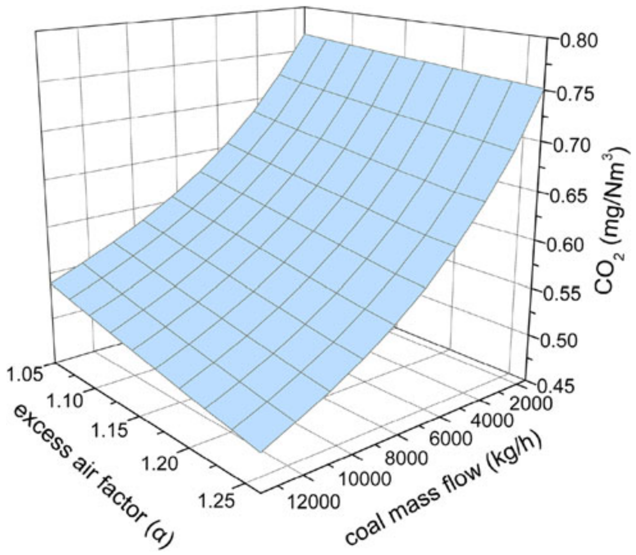

Fig. 7 Effects of the flow rate of coal and excess air factor on CO_2 in flue gas

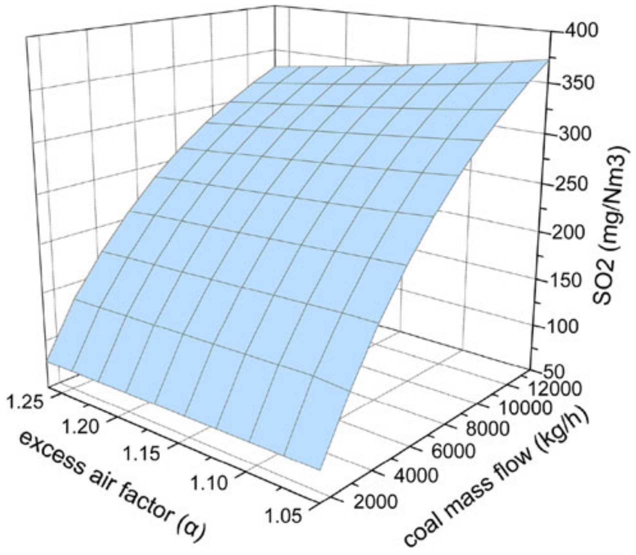

Fig. 8 Effects of the flow rate of coal and excess air factor on SO_2 in flue gas

not change the decomposition rate of raw materials. In this case, the amount of the flue gas rises sharply and a large share of CO_2 in the flue gas comes from the decomposition of the raw materials.

The conclusion from the above analysis is that the concentration of all kinds of pollution products in the flue gas can be controlled effectively by adjusting the flow rate of the coal entering the calciner, and controlling the combustion environment in the calciner. For example, reasonable division of the combustion environment in the calciner enables parts of the coal combustion reactions to take place in weak reductive conditions, which significantly reduces the emission of CO, NO, and SO_2. In industries, staging combustion technology is usually employed to control the formations of NO_x (Iliutaa et al. 2002; Hu 2004), but some difficulties still exist in determining proper percentages of the air staging and fuel staging, due to the complexity of the actual operations and the differences in the various production processes. To address this problem, an air staging module is added into the original model in the following section, to extend the individual air staging model which can be used to select the appropriate staging combustion plans.

Applications of the calciner process model

The calciner process model set up in Fig. 3 can not only provide data support for the cement industry in adjusting the input parameters of the calciner, but can help optimize the staging combustion plans by adding the air staging module into the original calciner process model.

The staging combustion technology is an effective method to improve the combustion operation in the calciner, which implies the staging combustion of tertiary air and fuels entering the calciner, including three specific plans: single air staging, single fuel staging and simultaneous air, and fuel staging (Hu 2004). Air staging means adding the tertiary air into the calciner by stages (shown by arrow ① in Fig. 2) to make fuels combust initially in weak reductive conditions with high temperature and insufficient oxygen, then proceed to further combustion in a low-temperature and oxygen-rich environment, in which formations of large amounts of fuel NO_x and thermal NO_x are effectively suppressed. Similarly, fuel staging means adding fuels into the calciner in stages (shown by arrow ② in Fig. 2) to form several combustion regions. In general, a large percentage of fuels are added to the main combustion region (Section II), and this ensures combustion reactions in this zone take place with enough oxygen. Meanwhile, a small amount of fuels are added into the pyrolysis and combustion region (Section I) to combust with insufficient oxygen, which will not simply control the large amount of NO_x generated during the combustion process, but reduce some of the NO_x coming from the rotary kiln. This article is only concerned with the case of single air staging.

Single air staging model of the calciner

The single air staging model is shown in Fig. 9, which is based on the original calciner process model proposed in Fig. 3 with the air staging module added in.

Comparing the model shown in Fig. 9 with the model displayed in Fig. 3, two reactor modules (FIRCOMB and SECCOMB) are used to simulate the combustion process of pyrolysis products, implemented by the RGIBBS and RSTOIC modules. The combustion reaction formulas of the primary combustion products such as CO and H_2 are set in SECCOMB simultaneously. Furthermore, a FSPLIT module and a MIXER module are added in the air staging model indicated by FSPLIT and MIXHEAT in Fig. 9, which are separately used to simulate the distributions of the tertiary air and the mixers of the reactor heat. The operation parameters of the newly added combustion reactor are the same as COMBUST shown in Fig. 3, and the pressure drops of FSPLIT and MIXER are both set at zero.

Optimization of the proportion of air staging

Taking the 2500t/d DD-calciner (Ex.1), for example, and changes in the excess air factor (α) in the first combustion zone, the outlet temperature of the calciner and the components of the flue gas caused from single air staging are studied by running the model shown in Fig. 9. Figures 10, 11, and 12 display the model results. In the simulation, proportion of air staging refers to the amounts of tertiary air entering into the pyrolysis and combustion region

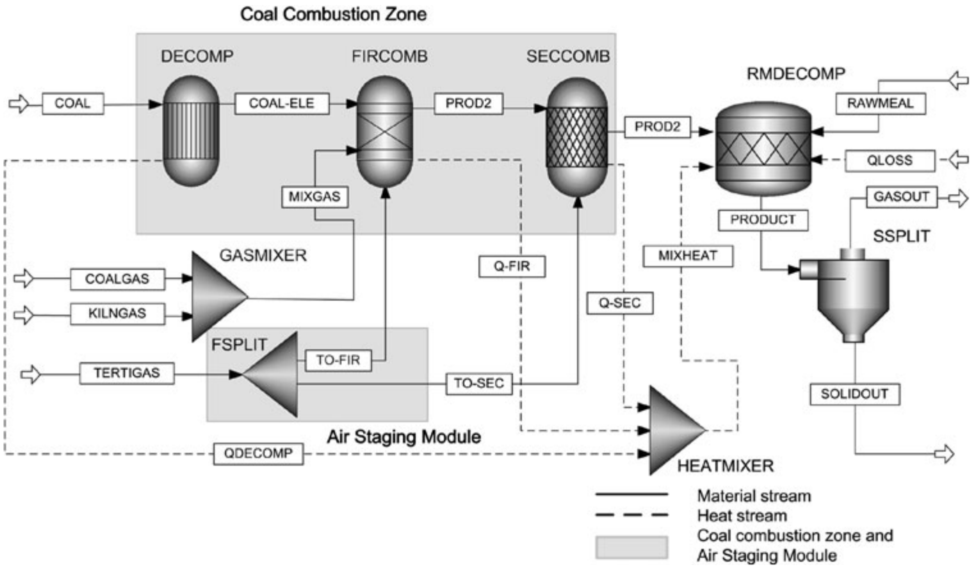

Fig. 9 Single air staging model

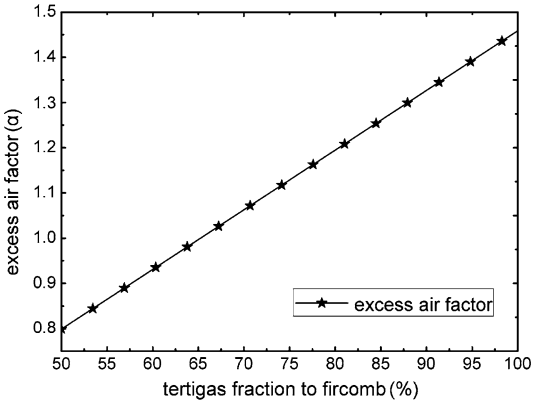

Fig. 10 Changes in the excess air factor in the first combustion zone with varying proportion of air staging

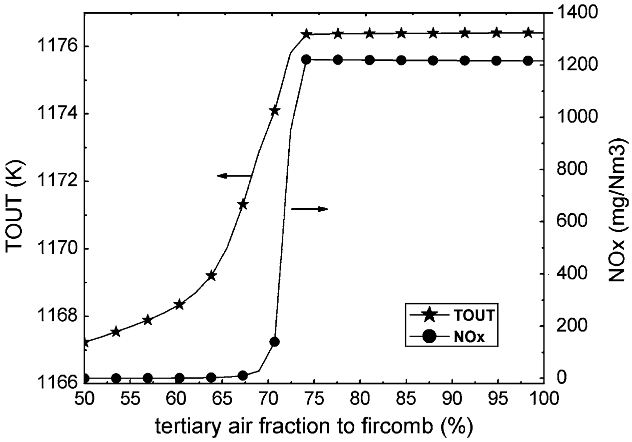

Fig. 11 Changes in the outlet temperature and NO_x concentration with varying proportion of air staging

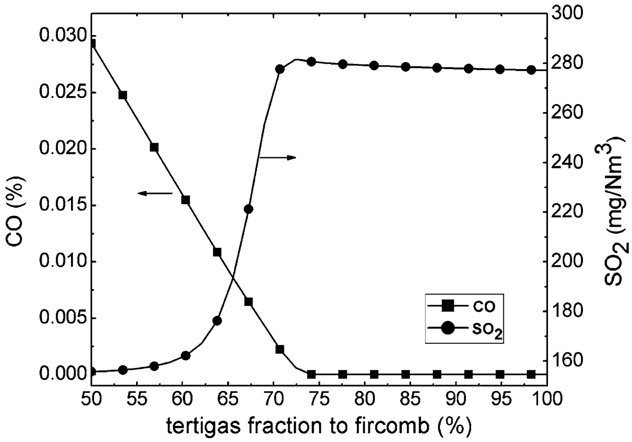

Fig. 12 Changes in CO and SO_2 concentration with varying proportion of air staging

(Section I, expressed by FIRCOMB in the model and called the first combustion zone), ranges from 50 to 100%, and is indicated by setting the parameter f_1 in FSPLIT. The concentrations of NO_x, CO, and SO_2 are converted to the values under standard conditions, and the NO_x content is expressed as 1.53 times the NO concentration (GB 4915-2004 2004).

Figures 10, 11, and 12 show that the excess air factor in the first combustion zone is positively correlated with the proportion of air staging f_1, and the outlet temperature changes little when f_1 varies. For the NO_x in the flue gas, when f_1 changes in the range of 50 to 69% ($0.8 < \alpha < 1.05$), the NO_x concentration approaches zero. Meanwhile, the NO_x content increases sharply when f_1 rises from 70.69 to 74.14% (α rises from 1.07 to 1.12), but does not change further when f_1 exceeds 74.14%. The CO concentration changes correspondingly as f_1 varies, and approaches zero when f_1 exceeds 72.41% ($\alpha > 1.095$). The SO_2 concentration has a similar change trend to NO_x. When f_1 rises from 63.8 to 65.52% (α rises from 0.98 to 1.004), the SO_2 concentration increases rapidly but the value is still at a comparatively low level. The SO_2 concentration rises to a fairly high value when f_1 increases from 65.52 to 70.69% (α increases from 1.004 to 1.07).

Combining the analysis above with the maximum allowable emission concentrations of SO_2 and NO_x in a cement kiln system, set in the *Emission Standards for Air Pollutants in the Cement Industry* of china (SO_2 200 mg/Nm^3 mix and NO_x 800 mg/Nm^3 mix), and the explosion limit concentration of CO (0.02 %) stipulated for precipitators in the cement industry, three conclusions are arrived at:

(1) The NO_x concentration changes slowly at a comparatively low level when f_1 varies in the range of 50 to 70.69%. The NO_x concentration increases rapidly and exceeds 800 mg/Nm^3 while f_1 is above 70.69%. For this reason, in order to keep the NO_x concentration up to the specification in the *Emission Standards for Air Pollutants in the Cement Industry* of china, the proportion of air staging f_1 should be controlled to less than 70.69% ($\alpha < 1.07$).

(2) The CO concentration changes correspondingly as f_1 varies. Increases in the proportion of air staging cause the CO concentration to decline when f_1 rises from 50 to 75%. When f_1 exceeds 57%, the CO concentration does not exceed the explosion limit concentration of CO (0.02%), so f_1 should be controlled to more than 57% ($\alpha > 0.89$).

(3) Increasing the proportion of air staging causes the SO_2 concentration to increase when f_1 rises from 50 to 73%. The SO_2 concentration increases rapidly and exceeds 200 mg/Nm^3 when f_1 is above 65.52%. Therefore, to keep the SO_2 concentration up to the

specification in the *Emission Standards for Air Pollutants in the Cement Industry* of china, the proportion of air staging f_1 should be controlled to less than 65.52% ($\alpha < 1.004$).

In conclusion, if the single air staging combustion plan is applied in this 2500t/d DD-calciner, the proportion of air staging should be controlled within the range of 57 to 65.52% ($0.89 < \alpha < 1.004$), so as to meet specifications for the NO_x and SO_2 content in the *Emission Standards for Air Pollutants in the Cement Industry* of China and the safety requirements for CO in equipment. In the actual industry, reasonable adjustments can be made according to the outlet temperature of the calciner.

Other applications

Apart from optimizing staging combustion plans by adding an air staging module and a fuel staging module to the original model, the calciner process model can be applied in the following situations.

(1) Studying the influences of alternative fuels and raw materials on the flue gas composition, the outlet temperature of calciner and the process energy consumption etc.
(2) Modifying the original model by adding NO_x and SO_2 removal modules and studying the influences of the amount of removal materials (such as carbamide and quicklime) and the reaction conditions on the removal efficiency.
(3) Computing the mass and energy balance during Cleaner Production Audits, Environmental Impact Assessment and Life Cycle Assessment of the entire production process for cement industries, which avoids the complexity of manual calculations.

Conclusions

In recent years, the pre-calcining kiln system has become one of the main emission sources of greenhouse gases (mainly CO_2) and acidic gases (mainly NO_x and SO_2) and must be taken seriously. Because of the operation traits of the pre-calcining kiln system, the task of maintaining the formation of pollutant gases will be completed in the calciner. Based on the specific analysis of the DD-calciner, this article divided the physical and chemical reaction processes of this type of calciner into several stages, simplified the calcination process using the Aspen Plus process simulation software, and established the calciner process model in Aspen Plus. Convenient analysis tools like the sensitivity analysis module, case study module, and design specification module of the model could be used to study key operation and design parameters which influence the flue gas composition. This could provide data support for the cement industry in adjusting input and facility parameters and reducing pollutants emission. The staging combustion program widely used to control the formation of NO_x in cement industries, the modified calciner process model could be applied to determine the most appropriate proportions of the staging combustion. Verified by industrial data, the calciner process model proposed in this article could replace most experiments and be used in simulation studies of the actual industrial process, which has significant benefits for the optimizing of the process and facility parameters and the filtering of the pollution reduction programs.

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