

NUMERICAL SIMULATION OF CO-COMBUSTION OF BIOMASS AND PULVERIZED COAL IN A PRECALCINER

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As high energy consumption and pollution increase in the cement industry, utilizing biomass as a substitute fuel has been deemed a promising energy-saving and emission reduction measure. Currently, research on the mixed burning of coal and biomass has mostly been done at the experimental level, providing limited guidance for actual production. Therefore, this paper investigates the mixed burning of coal fines and corn straw in a TTF-type precalciner by combining real production data and (CFD) numerical simulation methods. The influences of different corn straw blending ratios on the performance of precalciner are explored. The results show that, compared with non-corn straw, as the blending ratio of corn straw increases, the high-temperature zone inside the precalciner significantly shrinks. The maximum temperature of the furnace decreases to 1370K, the export raw material's decomposition rate decreases to 83.92%, and the concentration of NO drops to 464 ppm when 40% corn straw is blended. After comprehensive consideration, it is found more suitable to mix 30% corn straw. Compared to experimental studies, this study has more practical guidance significance for cement enterprises seeking to utilize biomass alternative fuels.

Key words: Biomass; Alternative fuel; Mixed combustion; precalciner; Numerical simulation.

1. Introduction

Cement production, a high energy consumption and pollution process, consumes approximately 12% to 15% of overall industrial energy consumption and constitutes around 7% of total global carbon emissions[1, 2]. Furthermore, cement production generates significant amounts of NO_x, SO₂, and PM, which worsen air quality and the ecological environment[3, 4]. Reducing energy consumption and pollution emissions while maintaining production capacity is vital in the cement industry. Among various strategies, utilizing alternative fuels is often regarded as one of the most promising techniques for saving energy and reducing emissions. This approach can significantly reduce dependence on fossil fuels and decrease greenhouse gas and pollutant emissions.[5, 6].

Among numerous alternative fuels, biomass has received much attention due to its renewability[7] and low-carbon characteristics[8]. As one of the countries with the richest biomass resources in the world, China produces about 1.04 billion tons of various agricultural waste annually[9]. These considerable biomass resources have enormous development potential. The application of biomass as a substitute fuel in the cement industry has various advantages. First, biomass features low-carbon, low nitrogen, and low pollution[10]. Second, biomass has a higher

volatile content and a faster combustion rate. Its high volatility allows it to release large amounts of volatile gases during heating. When co-combusted with coal, it can improve fuel ignition performance and effectively enhance combustion efficiency. Additionally, it can enhance the combustion characteristics of pulverized coal, thereby reducing instability during the combustion process[11, 12].

Currently, there have been many studies on biomass combustion and its co-combustion with coal. Yi et al.[12] utilized Thermogravimetric Analysis to investigate coal and biomass co-combustion in an O₂/CO₂ atmosphere. The study found that blending biomass improves coal combustion efficiency. Co-combustion of various biomass and coal had a considerable boosting effect, but the influence between different biomass was limited. Sun et al.[13] simulated the mixed combustion of coal and biomass in a 300MW coal fines boiler. They discovered that the co-combustion process reduced the peak temperature within the furnace and significantly decreased NO_x emissions. Jeong et al.[14] studied the kinetic characteristics of pyrolysis after blending coking coal and biomass. They found that as the ratio of biomass mixing increased, the reactivity of the coal-biomass mixture increased, and the reaction activation energy decreased. Li et al.[15] investigated the effect of co-pyrolysis of coal and biomass in an inert atmosphere on nitrogen and sulfur release. They observed that the release of volatiles exhibited significant synergistic effects within the temperature range of 600 to 800°C. Yuan et al.[16] used a thermal analyzer to examine the mixed combustion properties of clean coal and biomass particles. They discovered that mixed combustion improves combustion performance, with a significant synergistic effect between the two. Mikulčić et al.[17] simulated three co-combustion scenarios of coal fines and waste wood in a precalciner. They observed that mixed combustion decreases pollutant emissions. Ghenai et al.[18] conducted a numerical simulation study on the co-combustion of coal and biomass, and found that co-combustion can reduce NO_x and CO₂ emissions. Wang et al. [19] conducted a numerical simulation study on biomass co-combustion under the oxy-MILD mode. The study found that the oxy-MILD combustion mode is more effective in reducing NO_x emissions. Jia et al. [20] investigated the co-combustion of biomass and coal gangue and found that this process can reduce NO and SO₂ emissions. Black et al. [21] simulated the combustion of coal and biomass in a 500 Mwe coal-fired boiler and explored the potential impact of fuel type and combustion atmosphere on boiler heat transfer characteristics. Kim et al. [22] research found that the mixture of coal and ash-free biomass exhibited the best combustion performance. Both Oladejo et al.[23] and Chansa et al.[24] studies found that coal and biomass co-combustion exhibited a synergistic effect.

The above review demonstrates that the majority of research on the co-burning of coal and biomass are conducted at the experimental level. However, the cement precalciner is a large reactor accompanied by numerous complex reactions, such as fuel combustion and coupled raw material decomposition[25]. This complexity making it challenging to investigate under laboratory conditions. Furthermore, experimental studies alone are insufficient to effectively guide actual cement production. Currently, there is limited research on the co-burning of coal powder and biomass in precalciner, which hinders the application of biomass in the cement industry. Based on the above research's insufficiency, this study combines actual production data. It employs computational fluid dynamics (CFD) numerical simulation methods to investigate the simultaneous burning of coal powder and corn straw in a TTF-type precalciner. The effects of different corn straw blending ratios on the temperature field, composition field, raw material decomposition, and NO_x compounds in the decomposition furnace are examined and analyzed in detail. The aim is to determine the optimal corn straw blending

ratio under permissible production conditions, providing technical guidance for practical production.

2. Simulation methods and mathematical models

2.1. Fundamental conservation equation

The combustion of coal fines is highly complex[26], and any flow problem must adhere to the laws of mass and momentum conservation[27]. Furthermore, in systems involving heat exchange, the law of energy conservation must also be followed. The corresponding equations are as follows:

(1) Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad \#(1)$$

Where, u , v , and w represent the velocity components in the x , y , and z directions, respectively (m/s); t denotes time (s); and ρ represents density (kg/m^3).

(2) Momentum conservation equation:

$$\left. \begin{aligned} \frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u \vec{v}) &= \text{div}(\mu \text{grad} u) - \frac{\partial p}{\partial x} + S_u \\ \frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v \vec{v}) &= \text{div}(\mu \text{grad} v) - \frac{\partial p}{\partial y} + S_v \\ \frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w \vec{v}) &= \text{div}(\mu \text{grad} w) - \frac{\partial p}{\partial z} + S_w \end{aligned} \right\} \quad \#(2)$$

Where, μ represents dynamic viscosity; p denotes the pressure on the fluid element; S_u , S_v , and S_w represent the source terms in the x , y , and z directions, respectively. These source terms include body force sources, fluid dynamic sources, and user-defined sources.

(3) Energy-conservation equation:

$$\rho c_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T) + \Phi + q_{rad} + q_{gen} \quad \#(3)$$

Where, c_p is the specific heat capacity at constant pressure ($\text{J}/(\text{kg} \cdot \text{K})$); T represents temperature (K); \vec{u} is the fluid velocity vector; k is the thermal conductivity ($\text{W}/(\text{m} \cdot \text{K})$); Φ is the viscous dissipation term; q_{rad} is the radiation term (W/m^3); q_{gen} is the internal heat source term (W/m^3).

2.2. Gas-phase turbulence model and Particle motion model

Considering the possibility of complex flows such as secondary flow and swirl within the precalciner. This study employs the Realizable $k - \varepsilon$ model with swirl correction[28], which effectively simulates complex flows such as secondary flow and swirl. k represents turbulent kinetic energy, while ε represents its dissipation rate. The standard equation for the $k - \varepsilon$ model is as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k \mu_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad \#(4)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon \mu_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) + S_\varepsilon \quad \#(5)$$

Where, G_b stands for buoyancy-induced turbulent kinetic energy and G_k for the average velocity gradient-driven turbulent kinetic energy; the impact of pulsation expansion in compressible

turbulent flow is represented by Y_M . The Planck constants for dissipation rate and turbulent kinetic energy, respectively, are σ_k and σ_ε ; S_k and S_ε are specified source terms; while $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are empirical constants.

In this work, the motion of the particles inside the furnace is simulated employing the Discrete Phase Model (DPM). The DPM is based on a stochastic trajectory model from the Lagrangian perspective and simulates the motion process of particles[29]. The motion equation for particles under the random orbit model is as follows:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \quad \#(6)$$

Where, $F_D(u - u_p)$ represents the gravitational force exerted on particles per unit mass (N/kg); u denotes the gas phase velocity (m/s); ρ_p indicates the density of particles (kg/m³); g_x represents the acceleration due to gravity (m/s²); and F_x denotes the sum of all forces acting on a particle, except for gravity and gravitational force (N).

2.3. Particle combustion model

Upon entering the furnace, coal fines and biomass undergo thermal decomposition, releasing volatile substances and producing coke. This work simulates the precipitation of volatile components in coal fines and biomass using a two-step competition rates model. The model adopts a segmented solution method to obtain the precipitation rate of volatile matter in different temperature ranges, and its expression is as follows[30]:

$$R_1 = A_1 e^{-(E_1/RT_p)} \quad \#(7)$$

$$R_2 = A_2 e^{-(E_2/RT_p)} \quad \#(8)$$

Where, R_1 and R_2 represent the competitive reaction rate coefficients obtained by controlling volatilization analysis under different temperature ranges. The combustion of leftover coke after volatilization analysis is simulated employing the Kinetics/diffusion-limited reaction rate model. The pace at which oxygen molecules arrive at the coke surface (D_0) and the rate at which coke and oxygen molecules react (K) once they do so both affect the coke's combustion rate[31]. The expression for this model is given as follows:

$$\frac{dm_p}{dt} = -A_p P_{OX} \frac{D_0 K}{D_0 + K} \quad \#(9)$$

$$D_0 = C_1 \frac{[(T_p + T_\infty)/2]^{0.75}}{d_p} \quad \#(10)$$

$$K = C_2 e^{-(E_2/RT_p)} \quad \#(11)$$

Where, A_p stands for the particle's surface area; P_{OX} for the gas surrounding the particle's partial pressure; d_p for the particle's size; and the temperatures of the surrounding gas and the starting particle are denoted by T_∞ and T_p , respectively.

2.4. Raw material decomposition

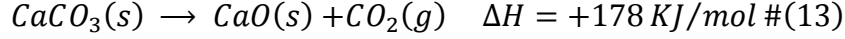
For raw material decomposition, the decomposition of CaCO_3 is simulated utilizing the Species Transport model and the Finite Rate/Eddy Dissipation model. The conservation equation for

component transport is as follows:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{v} Y_i) = -\nabla J_i + R_i + S_i \quad \#(12)$$

Where, Y_i indicates the mass fraction of substance i ; the net rate of chemical reactions is represented by R_i ; the rate of additional generation from discrete phase and user-defined source terms is represented by S_i ; the diffusion flux of substance i is denoted as J_i .

The decomposition reaction equation of CaCO_3 is expressed as follows:



The following equation is used to determine the rate of raw material decomposition:

$$\omega = \frac{m_1 - m_2}{m_1} \times 100\% \quad \#(14)$$

Where, the raw material inlet's total mass flow rate of CaCO_3 is represented by m_1 ; the mass flow rate of exit CaCO_3 is indicated by m_2 .

2.5. NO_x generation model

Regarding combustion, the generation of NO_x is mainly classified into three types: prompt NO_x , thermal NO_x , and fuel NO_x . Fluent provides models for these three types of NO_x generation. Considering that the amounts of prompt NO_x and thermal NO_x generated in the precalciner are minimal. This study mainly focuses on fuel NO_x to simulate the formation of NO_x in the precalciner. Fig. 1 shows the pathways for the generation of fuel NO_x . It is primarily assumed that the nitrogen in the fuel comes from volatiles and char. The nitrogen in the char can be directly converted to NO , while the nitrogen in the volatiles needs to be converted to NO via the intermediate HCN .

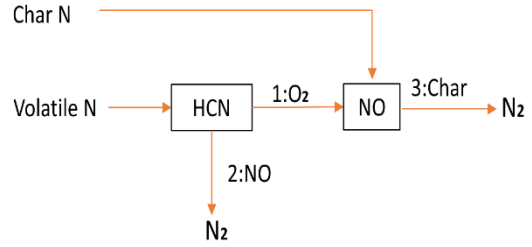


Fig. 1 Fuel NO_x generation pathway

2.6. Solution methods

This study uses ANSYS Fluent software for numerical simulations, employing the finite volume method to solve the governing equations. CFD code was used to solve the mathematical model. The SIMPLE algorithm is used for pressure-velocity coupling, and all discretization schemes are second-order upwind.

3. Basic information

3.1. Geometrical model and grid

This study focuses on the TTF-type precalciner of a 5000 t/d cement clinker production line in actual operation. The geometric model of the furnace is illustrated in Fig.2, which consists of a bottom cone, two necked portions, and three cylinders. The total height of the furnace is 45.88 meters, with a maximum diameter of 7.1 meters. The lower cone has a height of 5.6 meters, while the lower, middle, and upper columns have heights of 9.1 meters, 12.9 meters, and 8.22 meters, respectively. Four raw

material pipes are symmetrically distributed on the middle and lower columns, with two pipes on each column. Two tertiary air ducts are symmetrically positioned above the interface between the lower cone and lower column. Additionally, four coal (biomass) injection ducts are symmetrically placed above the tertiary air ducts.

A hexahedral grid structure was adopted for the precalciner simulation. Compared to tetrahedral meshes, hexahedral meshes offer better computational accuracy, mesh quality, computational efficiency, and stability. A non-uniform meshing strategy was employed in the model, with mesh refinement applied to specific regions (inlet and outlet) to ensure computational accuracy. Through multiple trials, the optimal number of mesh elements was selected to both maintain accuracy and reduce computational cost. To ensure grid-independent results, a grid independence study was conducted using five grid numbers: 818,800, 913,200, 1,032,000, 1,104,840, and 1,216,580. The predicted average outlet temperatures were compared with the actual outlet temperature, as presented in Tab.1. The results demonstrated that a grid number of 1,032,000 provided the closest agreement with the actual outlet temperature. Further increases in grid number yielded negligible changes in the predicted temperature. Consequently, the 1,032,000-grid configuration, depicted in Fig.3, was selected for subsequent simulations. All mesh qualities have a Determinant $2 \times 2 \times 2 > 0$, with the minimum being 0.45 and the smallest angle being 32° . This fully meets the computational accuracy requirements.

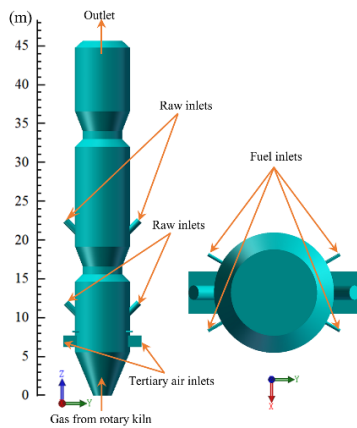


Fig. 2 Schematic diagram of the geometric model of the precalciner

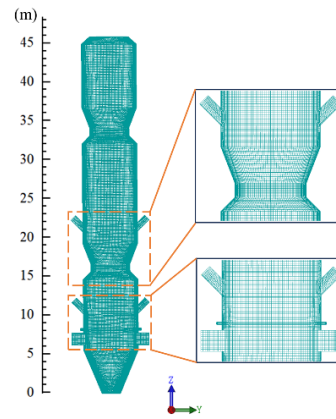


Fig. 3 Schematic diagram of the precalciner grid

Table 1 Average and actual temperatures at the outlet of precalciner with varying grid numbers

Number of Grids	818800	913200	1032000	1104840	1216580
Simulated temperature (K)	1120	1134	1154	1152	1150
Actual temperature (K)	1181	1181	1181	1181	1181

3.2. Material characteristics and boundary factors

The results of these analyses for coal and corn straw are presented in Tab.2, while the chemical compositions of the raw materials are listed in Tab.3. Powdered coal has particle sizes ranging from 5um at the least to 90um at the maximum and 65um at the average. The pulverized coal particles are spherical, with a density of 1400 kg/m^3 , a specific heat capacity of $1100 \text{ J/(kg}\cdot\text{K)}$, a volatile release temperature of 400°C , a particle expansion coefficient of 1.1, and an initial temperature of 337 K. The raw material's smallest, maximum, and average particle sizes are 20 um, 60 um, and 45 um,

respectively. The density of CaCO_3 particles is 2800 kg/m^3 , the specific heat capacity is $856 \text{ J/(kg}\cdot\text{K)}$, the thermal conductivity is $2.25 \text{ W/(m}\cdot\text{K)}$, and the initial temperature is 1040 K . A fixed particle size of $200 \mu\text{m}$ was assumed for the corn straw.

Five sets of operating conditions were established based on varying proportions of coal powder mixed with corn straw. The initial mass flow rate of pulverized coal was 4.8 kg/s , with corn straw replacing some of it in equal mass ratios (0%, 10%, 20%, 30%, and 40%). Only the mass flow rates of coal powder and corn straw being altered while all other operating parameters remained constant. The raw material inlet was specified as a mass flow inlet with a flow rate of 16.8 kg/s . The initial pressure is -2565 Pa , the turbulence intensity is 10%, and the hydraulic diameter is 0.85 m . The tertiary air velocity and temperature were set to 28 m/s and $1,300 \text{ K}$, respectively. The excess air coefficient is 1.189. The initial pressure is -348 Pa , the turbulence intensity is 10%, and the hydraulic diameter is 1.875 m . The kiln tail gas velocity and temperature were specified as 30 m/s and 1370 K , respectively. The initial pressure is -587 Pa , the turbulence intensity is 10%, and the hydraulic diameter is 2.4 m . A pressure outlet boundary condition was employed, with the exit pressure set at -1000 Pa . The backflow temperature is set to 1100 K , the backflow turbulence intensity is set to 10%, and the backflow hydraulic diameter is 5.1 m . The precalciner wall was assumed to be insulated. The main components of the rotary kiln exhaust gas were 11.3% CO_2 , 1.0% O_2 , 0.5% CO , and 87.2% N_2 . Under these conditions, no biomass was used in the rotary kiln.

Table 2 Coal and corn straw industrial and elemental analyses

Sample	Industry Analysis (%)				Elemental Analysis (%)					$Q_{net,ar}$ (MJ/Kg)
	M_{ad}	A_{ad}	V_{ad}	F_{Cad}	C_{ad}	H_{ad}	O_{ad}	N_{ad}	S_{ad}	
Coal	2.92	20.33	29.00	47.75	64.23	3.77	29.92	0.93	1.15	24.09
Corn straw	10.26	3.97	70.51	15.26	49.21	6.37	43.63	0.58	0.21	15.48

M – Moisture, A – Ash, V – Volatile, F – Fixed carbon, ad – Air-dry basis.

Table 3 Chemical composition of the raw materials

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Loss
Raw material (%)	11.76	3.69	2.76	42.83	1.30	35.28

3.3. Model verification

To assess the reliability of the simulation results, a comparison was performed between the predicted outlet values and the measured values obtained from the thermal calibration of the precalciner, as presented in Tab.4. The error between the simulated and measured values was found to be less than 5%, which falls within the acceptable range for engineering applications. This agreement confirms the reliability of the simulation results. Fig.4 shows the residual

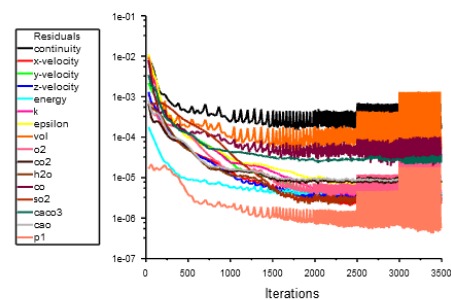


Fig. 4 Residual curve of the calculation

curves from the model calculations. As can be seen from the figure, after 2000 steps, the lowest points of each curve are nearly aligned. The residuals are all less than 10^{-3} , indicating that the computation has converged. This further confirms the reliability of the simulation results.

Table 4 Comparing the measured and simulated values at the precalciner 's outlet

Parameter	Biomass (%)	Simulation Value	Measured Value	Error (%)
Temperature(K)	0	1154	1181	2.29
CO ₂ Content (%)	0	25.44	26.3	3.27
O ₂ Content (%)	0	2.39	2.44	2.05

4. Simulation results and discussion

4.1. Combustion simulation under different corn straw blending ratios

4.1.1 Influence on the temperature field

Figure 5 illustrates the temperature contour map of the X=0 section in the precalciner with varying proportions of corn straw. The figure demonstrates that the high-temperature zone within the furnace is concentrated between the upper and lower raw material pipes and the lower cone section, exhibiting a symmetrical temperature distribution. The elevated temperatures between the upper and lower raw material pipes can be attributed to this region being the primary combustion area for the fuel, with ample oxygen supply. Upon entering the furnace, the coal powder and corn straw rapidly release volatile substances, and the volatile matter and fixed carbon undergo intense combustion, resulting in higher temperatures. The high-temperature flue gas coming from the kiln tail is what causes the high temperature in the lower cone section. The temperature distribution between the upper and lower raw material pipes exhibits higher temperatures on both sides and relatively lower temperatures in the central region. This is because the majority of the raw material from the lower raw material pipe decomposes in this middle area. The decomposition process of the raw material necessitates the absorption of a substantial amount of heat, leading to comparatively lower temperatures in the central section. Furthermore, as the proportion of corn straw replacing coal powder increases, the high-temperature zone between the upper and lower raw material pipes progressively narrows. Without biomass, the highest temperature in the precalciner is 1600K. When 40% corn straw is added, the maximum temperature gradually decreases to 1370K. Similarly, Sun et al.[13] in their study on the co-combustion of biomass and coal in a pulverized coal boiler also found that co-combustion reduced the peak temperature inside the furnace. The temperatures in the middle and upper columns also exhibit a slight decrease with the increasing proportion of corn straw replacing coal powder. The temperature at the precalciner outlet decreases from 1148K without biomass to 1141K when 40% corn straw is blended.

Figure 6 shows the average gas temperature at different heights in the precalciner when blending different proportions of corn straw. The figure reveals that, irrespective of the corn straw blending ratio, the furnace exhibits a consistent temperature change trend, characterized by an initial decrease, followed by an increase, and subsequently a decrease. This occurs because, after the flue gas from the kiln tail enters the furnace, the space rapidly expands, causing the average temperature to

drop. Then, as the coal and corn stalks combust, the temperature quickly rises. Finally, the raw material entering the furnace from the upper feed pipe absorbs a large portion of the heat for decomposition, resulting in another rapid temperature drop. Moreover, as the corn straw blending ratio increases, the $9.18 < Z < 18.35$ meter region of the furnace has a significant decrease in temperature overall. The average gas temperature at the outlet undergoes a slight decrease, which is consistent with the observations in Fig.5. This phenomenon may be attributed to the lower calorific value, higher moisture content, and reduced fixed carbon content of corn straw compared to coal powder. Specifically, the precalciner 's outlet gas's average temperature decreases from 1154K in the absence of biomass to 1152K, 1150K, 1147K, and 1145K when blended with 10%, 20%, 30%, and 40% corn straw, respectively.

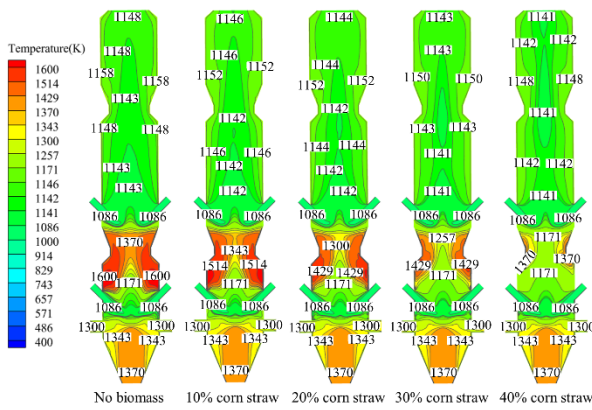


Fig. 5 Temperature contour map of the $x=0$ section in the precalciner under various corn straw blending ratios

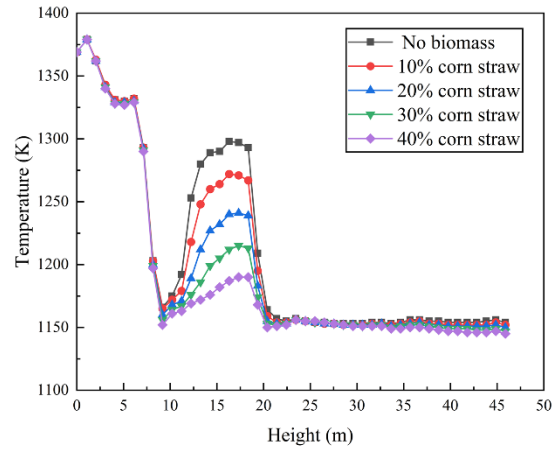


Fig. 6 Average gas temperature at various corn straw blending ratios along the precalciner 's height

4.1.2 Influence on raw material decomposition

Figures 7 and 8 illustrate the average mass fractions of CaCO_3 and CaO at different heights in the precalciner when blending different proportions of corn straw, respectively. The CaCO_3 mass fraction in the precalciner exhibits a consistent trend with height. This trend is characterized by an overall pattern of initial increase followed by a decrease, then another increase and subsequent decrease. The mass fraction of CaCO_3 increases twice, primarily due to the arrangement of two raw material pipes in the lower and middle sections of the precalciner. In contrast, the mass percentage of CaO on average demonstrates a gradual increasing trend with height. This illustrates the continuous breakdown of raw materials once they enter the furnace, with the average mass fraction of CaO reaching its maximum value at the precalciner 's outlet. In the range of $19.37 < Z < 20.39$ m, there is a brief decrease in the mass fraction of CaO . This is due to some CaCO_3 entering the furnace from the upper raw material pipe, which causes a dilution effect on the CaO mass fraction.

Additionally, as the proportion of corn straw replacing coal powder increases. The overall CaCO_3 mass fraction in the precalciner gradually increases at heights between 9.18 and 18.35 meters and above 20.39 meters. Meanwhile, the overall CaO mass fraction exhibits a gradual decrease. The increase in the proportion of corn straw replacing coal powder results in a gradual decrease in the

overall temperature inside the furnace. Consequently, this leads to a reduction in the decomposition rate of raw materials. Calculations reveal that the rates of CaCO_3 breakdown at the precalciner's outlet were found to be 92.31%, 90.21%, 88.40%, 86.31%, and 83.92% when corn straw was blended at ratios of 0%, 10%, 20%, 30%, and 40%, respectively. Considering the requirement in actual production to maintain the rate of raw material breakdown at the outlet of the precalciner between 85% and 95%. It is recommended to utilize corn straw as a replacement for pulverized coal at a ratio of 30%, which is more appropriate.

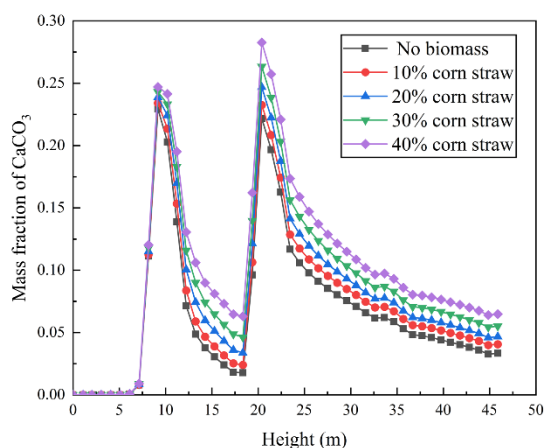


Fig. 7 average CaCO_3 mass fraction along the precalciner height for various corn straw blending ratios

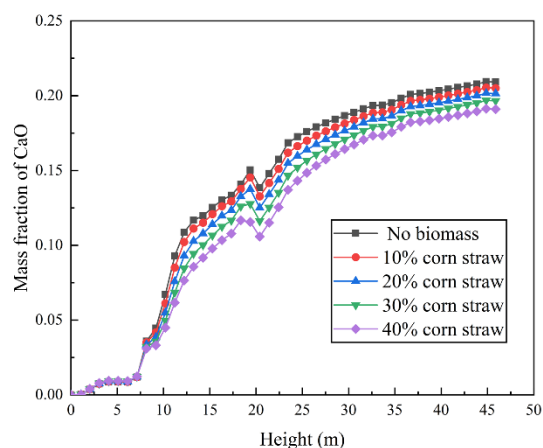


Fig. 8 Average CaO mass fraction along the precalciner height at various corn straw blending ratios

4.1.3 Influence on composition fields

Figures 9 and 10 show the distribution of O_2 and CO_2 on the $X=0$ section of the precalciner with varying corn straw proportions. These figures indicate that in the absence of biomass, the high concentration area of O_2 is concentrated near the tertiary air inlet, and as the height of the furnace rises, the O_2 concentration gradually decreases. In the main burning area, O_2 is rapidly and significantly consumed, while coal combustion and raw material decomposition release a substantial amount of CO_2 , resulting in a higher CO_2 concentration in this area. In the middle and upper columns, O_2 continues to be gradually consumed by unburned coal, resulting in a further drop in O_2 concentration and a rise in CO_2 concentration, with more CO_2 accumulating in the upper column. Moreover, the figures clearly show that as the proportion of corn straw replacing coal powder increases, the high concentration area of CO_2 in the main burning area is significantly reduced. At the same time, the high concentration area of O_2 is significantly increased. This phenomenon may be attributed to the higher oxygen and lower carbon content of corn straw in comparison to coal powder, requiring less O_2 and releasing less CO_2 for combustion. Furthermore, the reduction in the raw material decomposition rate also results in a decrease in the CO_2 released.

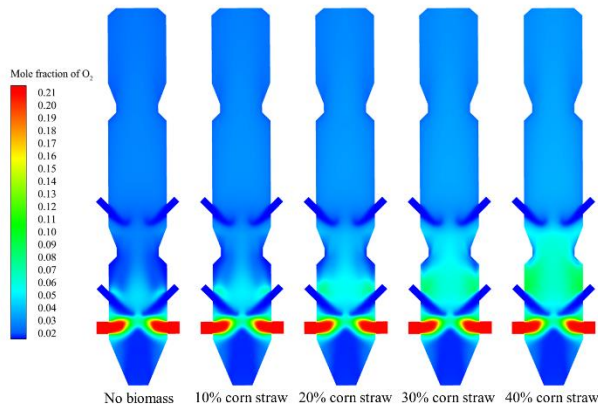


Fig. 9 O₂ distribution map on the x=0 section in the precalciner under various corn straw blending ratios

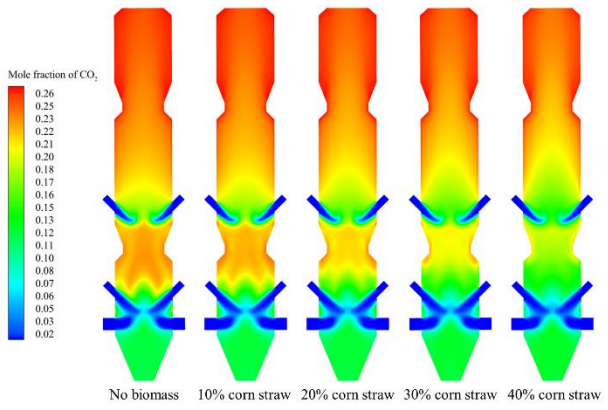


Fig. 10 CO₂ distribution map on the x=0 section in the precalciner under various corn straw blending ratios

Figures 11 and 12 illustrate the average mole fractions of O₂ and CO₂ at different heights in the precalciner when blending different proportions of corn straw, respectively. These figures demonstrate that the trend of changes in the mole percentage of O₂ and CO₂ is opposite, with the mole fraction of O₂ showing an initial increase followed by a decrease, while the CO₂ mole fraction initially decreases and then increases. This is because the introduction of tertiary air initially increases the O₂ concentration and decreases the CO₂ concentration. Subsequently, as combustion and raw material decomposition proceed, O₂ is gradually consumed and CO₂ is progressively produced. The mole percentage of O₂ reaches its lowest point at the outlet, while the mole percentage of CO₂ reaches its highest point. Additionally, as the proportion of corn straw replacing coal powder increases, the mole percentage of O₂ in the precalciner increases overall after Z>7.14m, while the mole percentage of CO₂ reduces overall. This corresponds to Figures 9 and 10. Specifically, the mole percentage of CO₂ at the exit decreased from 0.2544 without biomass to 0.2319 when mixed with 40% corn straw, indicating that replacing some coal powder with corn straw can reduce carbon emissions. Similarly, Ghenai et al.[18]observed in their numerical simulation study of coal and biomass co-combustion that co-firing can also reduce CO₂ emissions at the furnace outlet.

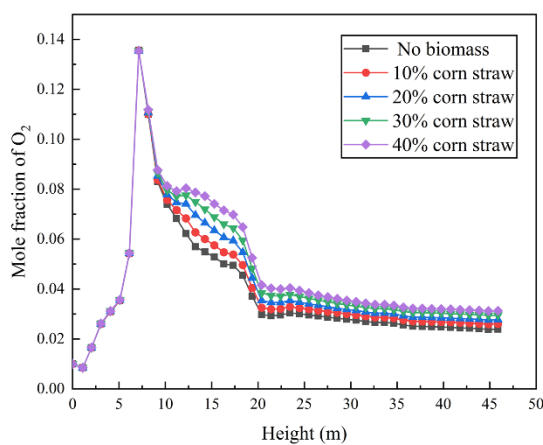


Fig. 11 Average O₂ mole fraction along the precalciner height at various corn straw blending ratios

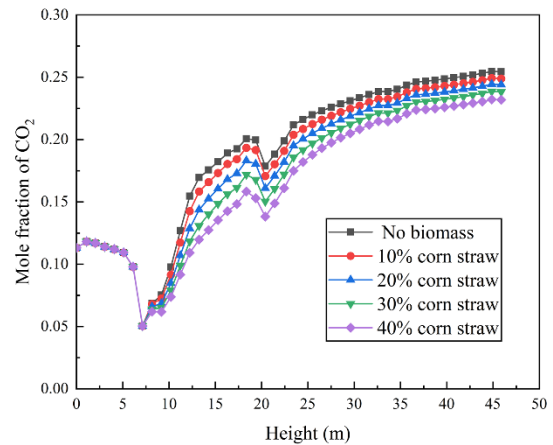


Fig. 12 Average CO₂ mole fraction along the precalciner height at various corn straw blending ratios

4.1.4 Influence on NO_x compounds

The two primary sources of NO_x in the precalciner are the fuel NO_x, which is formed by burning fuel, and the thermal NO_x, which is present in the high-temperature flue gas at the kiln tail. In this study, the nitrogen contained in the fixed carbon and volatile matter in the fuel is considered to simulate the formation of fuel type NO_x. Figure 13 illustrates the NO distribution on the X=0 section in the precalciner for various corn straw blending proportions. As indicated by Fig.13, the high concentration area of NO in the precalciner is primarily concentrated in the primary combustion area between the inlet of the kiln tail gas and the upper and lower raw material pipes. Furthermore, as the corn straw blending ratio increases, the high concentration area of NO in the main burning area significantly narrows, with the highest concentration of NO decreasing from 793 ppm without biomass to 477 ppm when blending 40% corn straw. This is mainly because corn straw have a lower nitrogen content. The center and upper columns' NO concentration progressively drop as the corn straw blending ratio rises.

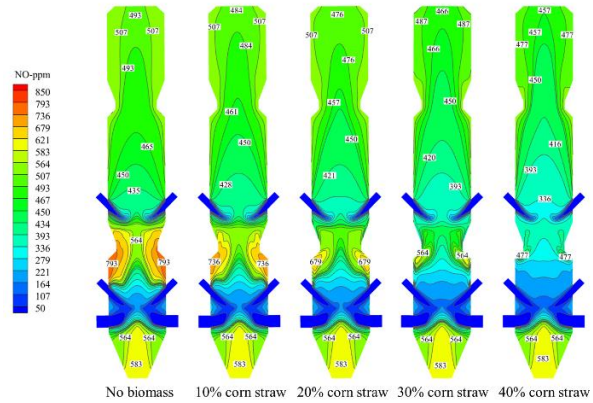


Fig. 13 NO contour map on the x=0 section in the precalciner under various corn straw blending ratios

Figure 14 presents the average concentration of NO at different heights in the precalciner when blending with different proportions of corn straw. As indicated by Fig.14, at the entrance of the kiln tail gas, the average concentration of NO reaches its maximum value of 583 ppm. Subsequently, as the height increases, the NO concentration rapidly decreases, reaching its lowest point at Z=9.18 m. This rapid decrease can be attributed to the significant dilution effect on NO concentration caused by the large amount of air entering from the third wind. After Z>9.18 m, the NO concentration rises rapidly again, peaking at Z=18.35 m. This increase is due to the rapid oxidation reaction between the fixed carbon and nitrogen in the volatile matter of the fuel and oxygen in the main combustion zone, leading to a continuous increase in NO concentration. At 18.35<Z<20.39 m, a brief decrease in NO concentration is observed, which can be attributed to the dilution effect of CO₂ generated by the decomposition of CaCO₃ entering the upper raw material pipe on the NO concentration. After Z>20.39 m, as the remaining nitrogen in the fixed carbon and volatile matter continues to oxidize, the NO concentration continues to increase with height and tends to stabilize. It is noteworthy that as the proportion of corn straw replacing coal powder increases, the overall NO concentration in the precalciner gradually drops. At the outlet, the average NO concentration dropped from 507 ppm without biomass to 495 ppm, 490 ppm, 476 ppm, and 464 ppm when mixed with 10%, 20%, 30%, and 40% corn straw, respectively. This finding suggests that

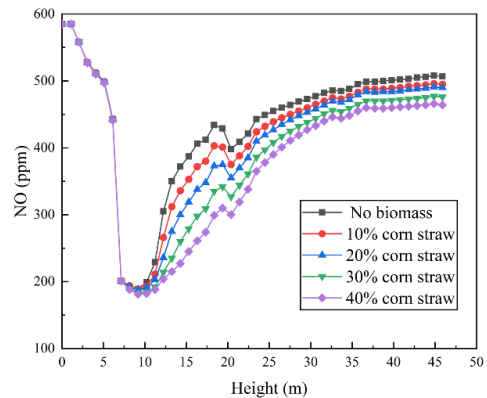


Fig. 14 NO concentration (ppm) at various corn straw blending ratios along the precalciner's height

replacing a portion of the coal powder with corn straw can effectively reduce the emission of nitrogen oxides. Both Ghenai et al.[18]and Wang et al.[19]in their numerical simulations of biomass and pulverized coal co-combustion, found that co-firing reduced NO_x emissions.

5. Conclusion

This study investigated the co-combustion of biomass and pulverized coal in a precalciner. Based on model validation and comparisons with existing research, the following conclusions and future directions are drawn:

(1) The blending ratio of corn straw significantly impacts the temperature distribution inside the precalciner. As the percentage of corn straw grows, the high-temperature zone shrinks, the peak temperature decreases, and the overall temperature inside the furnace gradually reduces. Without corn straw, the maximum temperature reached 1600K. However, when blended with 40% corn straw, the maximum temperature dropped to 1370K, and the average outlet gas temperature decreased from 1154K to 1145K.

(2) The decomposition rate of raw materials at the outlet of the precalciner is inversely proportional to the blending ratio of corn straw. Without corn straw, the decomposition rate was 92.31%. As the blending ratio increased to 10%, 20%, 30%, and 40%, the decomposition rates decreased to 90.21%, 88.40%, 86.31%, and 83.92%, respectively. The average mass fraction of CO₂ at the outlet also reduced from 0.2544 without corn straw to 0.2319 when mixed with 40% corn straw. Similarly, the average concentration of NO at the outlet decreased from 507 ppm without corn straw to 464 ppm when mixed with 40% corn straw. Considering both production requirements and pollution gas emission reduction, a blending ratio of 30% corn straw is deemed more appropriate.

(3) Since particle size directly affects combustion, further consideration can be given to the impact of biomass particle size on co-combustion. Additionally, the injection position of the biomass can also directly influence combustion within the furnace. It would be valuable to investigate the effects of adding biomass at different positions on the performance of the precalciner.

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