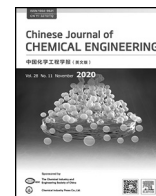




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Article

Numerical simulation on optimization of structure and operating parameters of a novel lean coal decoupling burner

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ABSTRACT

Due to its low volatile characteristics of lean coal, it is difficult to catch fire and burn out. Therefore, high temperature is needed to maintain combustion efficiency, while, this leads to high nitrogen oxide emission. For power plant boilers burning lean coal, stable combustion with lower nitrogen oxide emission is a challenging task. This study applied the 3D numerical simulation on the analysis of a novel de-coupling burner for low-volatile coal and its structure and operation parameters optimization. Results indicate that although it was more difficult for lean coal decoupling burner to ignite lean coal than high volatile coal, the burner formed a stepwise ignition trend, which promoted the rapid ignition of lean coal. Comparison of three central partition plate structure shows that in terms of characteristics of the flow field distribution, rich and lean separation and combustion, the structure with an inclination of 0° showed good performance, with its rich-lean air ratio being 0.85 and concentration ratio being 22.94, and there was an apparent decoupling combustion characteristic. Finally, the structure of the selected burner was optimized for its operational conditions. The optimal operating parameters was determined as the primary air velocity of 24.9 m·s⁻¹ and the mass flow rate of pulverized coal of 2.5 kg·s⁻¹, in which the pyrolysis products were utilized as reductive agent more fully. Eventually, the nitrogen oxide was efficiently reduced to nitrogen, which emission concentration was 61.88% lower than that in the design condition.

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1. Introduction

Due to the difficulty of fuel ignition and burnout, the combustion temperature in boilers burning low volatile coal is higher than general pulverized coal furnace, resulting in higher nitrogen oxide (NO_x) emission concentration [1]. In China, with the in-depth implementation of the action plan on coal power energy saving, emission reduction, as well as upgrading and transformation, NO_x emission is required to be less than 50 mg·m⁻³. Therefore, the de-nitration technology of boiler burning low volatile coal is facing a huge challenge of upgrading and transformation [2]. In order to solve these problems, it is necessary to explore the combustion technology that can eliminate the contradiction between lean coal combustion efficiency and NO_x emission control [3].

The low nitrogen (low-NO_x) burner has been developed for more than one hundred years, with various principles and types. It can be used in combination with air-staged combustion, fuel-staged combustion, flue gas re-burning and other technologies. Different burners could be used for appropriate coal types and furnace types. The mature stable-combustion technology of burner is mainly realized by means of rich-fuel/lean-fuel combustion, enhanced hot reflux and enhanced

initial combustion. The main technologies are divided into three categories: (1) the flow characteristics of the primary air in the horizontal burner are changed by the block causing the flue gas backflow, such as the blunt body burner, the slit blunt body burner [4], and the stable combustion chamber burner [5]; (2) using the swirling flow to produce the central reflux area, such as swirling burner [1,6]; and (3) generating reflux zones by combined jets, such as high-velocity differential burner [7] and offset jet burner.

Compared with the direct current burner (horizontal burner) [8], the swirl burner [9] has more functions of internal reflux, and the internal and external reflux zone increases the range of low-speed flow zone, which is more conducive to ignition [10]. However, due to the existence of radial and tangential velocity, the rigidity of axial jet flow is weakened and the penetration distance is limited. At the same flame temperature, the thicker the flame, the stronger the radiation capacity is. The weak rigid airflow limits the radiation capacity of the flame, which decreased the support effect of the swirl burner to the combustion in the later ignition stage. Zhou *et al.* developed the adjustable adaptive burner, which is a combination of horizontal and swirl burner [6]. It combines the strong rigidity of the horizontal burner and the reflux effect enhancement of the swirl burner. Part of the primary air flows through the horizontal nozzle and directly flows into the furnace, which guarantees the penetration distance. Nevertheless, the other flows pass the

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outer ring and enter furnace with spiral flow, in order to increase reflux and entrainment.

In order to meet the requirement of low- NO_x combustion, the pulverized coal burner needs to generate low NO_x while intensifying ignition. Zeng *et al.* pointed out that the bias coal combustion, in other words, the rich/lean combustion technology and the hot reflux swirl burner not only helped stabilize combustion, but also reduced NO_x [11]. The swirl burner can not only bring conditions conducive to ignition, but also effectively control the generation of NO_x by adjusting the air flow ratios of internal and external secondary air and the appropriate swirl intensity [12]. To some extent, it could achieve the stable combustion and low- NO_x emission effect through the efficient concentration of pulverized coal [13]. The fuel-rich and oxygen-poor combustion of the concentrated pulverized coal flow in the horizontal rich/lean burner is beneficial to control the generation of fuel-nitrogen [14]. Compared with the swirl burner, it is a simple and high efficient low- NO_x and stable combustion burner.

Although the research scholars have developed a variety of burners suitable for burning low volatile coal, owing to the increasingly tightened environmental standards and gradually strengthened power grid-load changes, it is still a challenge to guarantee the stability of lean coal combustion in the meantime lowering the NO_x emission. Therefore, the burner should be further improved according to the theory of NO_x generation and control. The horizontally rich/lean burners can provide favorable conditions for the ignition of pulverized coal only rely on the simple structure, which is very beneficial to improve the ignition stability of lean coal. In this paper, a novel decoupling burner for lean coal was developed based on the horizontal rich/lean pulverized coal burner. The combustion mode numerical simulation method is utilized to analyze the stable-combustion and low nitrogen principle of this decoupling burner. In addition, the structure of this burner and operation parameters is optimized.

2. Physical Model of Decoupling Burner

According to the formation mechanism of fuel NO_x , NO_x generated in the process of coal burning is mainly derived from oxidized NO formed through the oxidization of nitrogen in the fuel, and its generation process is in competition with the reaction in which it is transformed to N_2 by the nitrogen intermediate. The pyrolysis gas components of CO, H_2 , NH_3 , HCN and C_nH_m have strong reducibility to NO_x [15]. The basic principle of decoupling combustion technology is to reduce the nitrogen intermediate to N_2 using pyrolysis products of the coal itself, on a favorable condition strengthened by dividing the coal combustion process into two stages: (1) oxygen-deficient pyrolysis and NO_x reduction, and (2) coke oxygen-enriched burnout. In these two processes, the coal firstly undergoes oxygen-deficient environment, which significantly reduces the possibility of volatile nitrogen being oxidized into NO. After that, the reducing gases first pass through the semi-coke layer and then enter the main combustion area with sufficient air. In the semi-coke layer, NO_x reduction reaction of homogeneous and heterogeneous phases is developed [16,17]. In conclusion, to achieve the effect of fully reducing nitrogen by decoupling combustion, coal pyrolysis needs to be strengthened so that pyrolysis gas with enough concentration can fully contact and react with the NO_x generated in the semi-coke layer. Therefore, good pulverized coal concentrator and flame stability structure are the critical parts of a decoupling burner. The structure of the horizontal decoupling burner suitable for low volatile coal studied in this paper is shown in Fig. 1.

Same as the conventional horizontal fuel rich/lean burner, the decoupling burner nozzle was separated to left and right two sides, which go through the high and low concentration pulverized coal streams separately. Different from the blunt body burner and the stable combustion chamber burner, which uses blunt body or chamber as the flame holder, a stepped powder collecting flame holder is designed at the outlet of this novel decoupling burner to realize the decoupling

combustion. The stepped powder collecting flame holder located in the rich-side channel was used to change the flow state and temperature distribution of the burner nozzle area, delay the mixing of rich and lean pulverized coal streams, and ensure a gradual ignition of the fuel from rich to lean side, so as to improve the decoupling combustion effects in the small space inside the primary air as well as before the mixing of the secondary air.

3. Numerical Simulation of Combustion

3.1. Meshing method

A 3D modeling was performed by simulation computation according to the actual burner size of a boiler in a power plant. The total length from the inlet of the burner separator to the burner nozzle was 1.99 m, and the burner nozzle was 0.6 m high and 0.49 m wide. In order to analyze the burner's field distribution of jet velocity, temperature and component concentration, a simulated furnace space with a width of 13 m as exhibited in Fig. 2 was built in front of the burner. Together with meshing of the computational domain and spatial dispersion of flow region, the cutcell method was adopted to generate a hexahedral-based mesh. In order to adapt to the complex structure of the separation structure in the burner and near the burner nozzle, the mesh local refinements were carried out. Taking the outlet cross section of the burner as the check surface, the grid independence test was carried out on the partitioned mesh with average velocity and average particle concentration on the surface, and there were altogether 454,047 grids generated. The meshing views from all directions are shown in Fig. 3.

3.2. Mathematical model

The ANSYS FLUENT was employed for the numerical simulation of the three-dimensional gas–solid two-phase flow of the burner. During combustion, Realizable k - ε model was adopted for gas-phase turbulent flow model, while the Lagrangian method and discrete phase model were adopted for gas–solid two-phase turbulent flow model, and a stochastic tracking approach was applied to particle tracking. The interaction between turbulence and chemistry was considered using Mixture-Fraction PDF model. P1 model was selected to simulate radiation heat transfer. The particle combustion model and NO_x generation model are described in detail below.

(1) Particle combustion model

Pulverized coal combustion process is divided into de-volatilization, volatiles combustion, coke combustion and other processes. The source term in the one-order differential equations, energy equation and component equilibrium equation is given together by the volatile pyrolysis model and the coke particle combustion model.

1) Pyrolysis volatile model of coal

The two competing-rate models are a mode that has been widely applied due to simple computation and relatively accurate results. In this model, two parallel and competing first-order reactions (Eqs. (1) and (2)) are used to describe the release process of volatiles.

$$R_1 = A_1 e^{-(E_1/RT_p)} \quad (1)$$

$$R_2 = A_2 e^{-(E_2/RT_p)} \quad (2)$$

In the equations, R_1 and R_2 are the reaction rates of the two reactions controlling volatiles release at different temperatures. The proportion of the two reaction rates is measured according to Eq. (3).

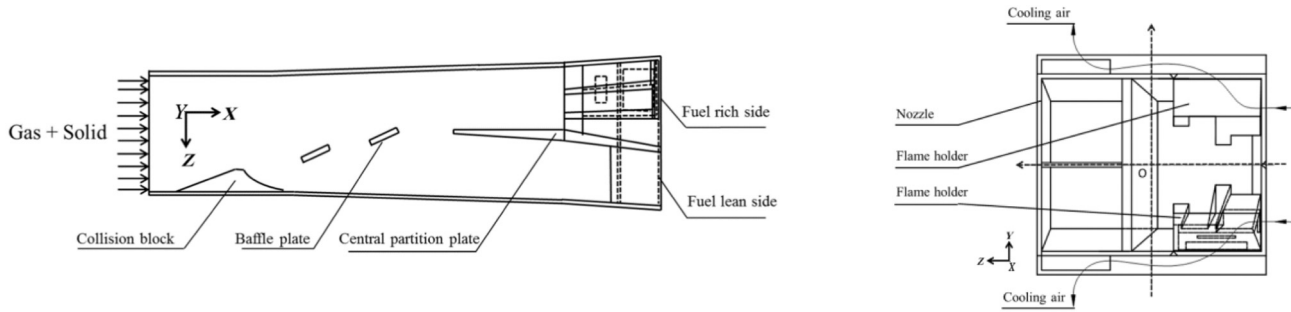


Fig. 1. Diagrams of (a) lean coal decoupling burner and (b) nozzle.

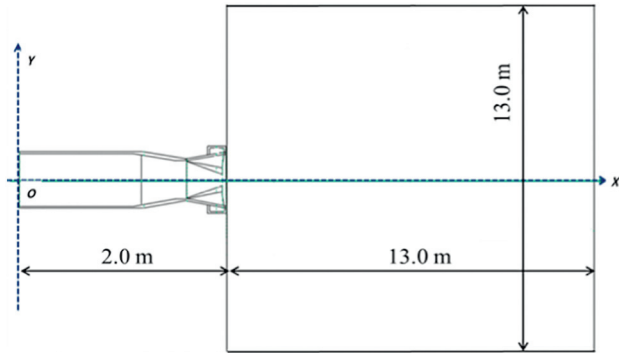


Fig. 2. The calculation domain structure and size of the burner.

$$\frac{m_v(t)}{[(1-f_{w,0})m_{p,0}-m_a]} = \int_0^t (\alpha_1 R_1 + \alpha_2 R_2) \exp\left(-\int_0^t (R_1 + R_2) dt\right) dt \quad (3)$$

In the equation, $m_v(t)$ is the release amount of volatiles over time, $m_{p,0}$ is the initial particle mass in the jet flow, α_1 and α_2 are the respective yield factors of the two reactions, and m_a is the ash content in the particles. According to the literature, α_1 represents the reaction rate at low temperature and shall be set as the percentage of volatiles in coal industry analysis, and α_2 represents the reaction rate at high temperature.

2) Char combustion model

The kinetic/diffusion surface reaction rate model, proposed by Baum, Street [18] and Field [19], assumes that the surface reaction rate is determined by the kinetic reaction rate and the material diffusion rate.

Diffusion rate coefficient:

$$D_0 = C_1 [(T_p + T_\infty)/2]^{0.75} / d_p \quad (4)$$

Reaction kinetic rate:

$$R = C_2 e^{-(E/RT_p)} \quad (5)$$

The final burnout rate of char is determined by measuring the proportion of the two rates according to Eq. (6).

$$dm_p/dt = -A_p p_{ox} D_0 R / (D_0 + R) \quad (6)$$

In the equation, C_1 is the diffusion constant, C_2 is the kinetic constant, T_p is the temperature of coke particles, T_∞ is the temperature at infinity, A_p is the surface area of micro-droplet (πd_p^2), p_{ox} is the partial pressure of oxides from the gas around the burning coke, and R is the kinetic reaction rate formed based on the comprehensive consideration of the influence of chemical reactions on the inner surface of coke particles and pore diffusion. In this model, the density decreases with coke combustion, assuming that the particle diameter remains unchanged.

(2) NO_x generation and reduction model

The PDF transport equation model appropriately simplifies the detailed chemical reaction of NO_x generation and reduction, considering only the main reaction steps that control the system. The reducing action of hydrocarbon fuel on NO mainly depends on a series of complex chemical reactions between hydrocarbon radicals and NO. When methane is used as re-burning fuel, the overall rate of reduction reaction may be expressed as follows:

$$R_1 = (k_a x_1 + k_b x_i^2) [CH_4] [NO] \quad (7)$$

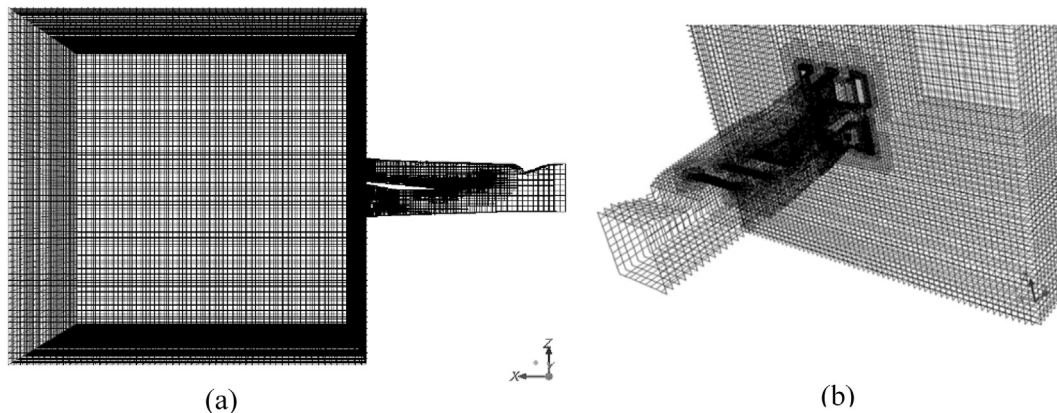


Fig. 3. Meshing of the burner model: (a) top view, (b) local view of the burner nozzle.

$$R_2 = k_c x_1^3 x_2 [\text{CH}_4][\text{NO}] \quad (8)$$

In the equations, k_a and k_b are the reaction rate constants, x_1 is the concentration ratio of hydrogen atom to hydrogen molecule, and x_2 is the concentration ratio of hydroxyl to water molecule. For gas re-burning, two items shall be added to the source term:

$$d[\text{HCN}]/dt = 4 \times 10^{-4} R_1 \quad (9)$$

$$d[\text{NO}]/dt = -4 \times 10^{-4} (R_1 + R_2) \quad (10)$$

In addition, the effects of turbulence on NO_x generation are simulated using a Beta PDF model with temperature fluctuation. The calculation was run firstly under default PDF point's value of 10 to convergence, and then the value was increased until the results stop changing. The temperature variance and $T_{\max}$ option were kept at the default selection as algebraic and global- $T_{\max}$ separately.

4. Boundary Conditions

The inlet conditions of numerical calculation were set according to the rated conditions of 330WM lean coal boiler in a power plant, and the mass flow rate was set according to actual fuel consumption. The boundary conditions adopted velocity inlet and pressure outlet. The gas velocity at the inlet of the primary air was set at $24.90 \text{ m} \cdot \text{s}^{-1}$ and the temperature was set at 220°C ; the boundary air velocity was set at $35 \text{ m} \cdot \text{s}^{-1}$; the pressure at the outlet was atmospheric pressure, the gas was under non-slip boundary conditions on the wall surface, and the particle was under the specular condition on the wall surface. The velocity of discrete phase particles was the same as that of the primary air, the temperature was the same, and the mass flow rate was $2.91 \text{ kg} \cdot \text{s}^{-1}$. The mixed particle diameters were set as Rosin–Rammmler distribution and were classified according to the sieving test data of the coal sample collected from the feeding bin of the power plant, with the minimum particle diameter being $1 \times 10^{-6} \text{ mm}$, the maximum particle diameter 0.0001 mm , and the median particle diameter $7.6 \times 10^{-5} \text{ mm}$. Uniform particle amount was set for each grid of the inlet cross-section, with the particle starting site in a single grid given randomly.

4.1. Proximate analysis of coal

In order to investigate the applicability of decoupling burner to lean coal, the thermal-state numerical simulation was carried out for burning both lean coal and high volatile coal. The industrial analysis results of the two coal samples are shown in Table 1.

4.2. Structure optimization of burner

At its inception, the burner was designed to tilt the central partition plate 10° to the fuel rich side within nozzle in order to increase the rich-side pulverized coal cascade change space, but the preliminary study found that the rich-phase pulverized coal stream of the burner tilted to the lean side [20]. Therefore, it was necessary to carry out detailed optimal computation on the angle of inclination of the central partition plate. Table 2 shows the parameters.

Table 1
Proximate analysis results of the samples

Sample	Proximate analysis/wt%				$Q_{\text{net,ar}}/\text{kcal} \cdot \text{kg}^{-1}$
	M_{ar}	A_{ar}	V_{ar}	FC_{ar}	
Lean coal	5.67	29.20	12.49	58.31	5497.00
High volatile bitumite	9.8	29.59	22.97	47.44	4825.41

Note: M_{ar} : moisture as received A_{ar} : ash as received V_{ar} : volatile moisture as received. FC_{ar} : fixed carbon as received; $Q_{\text{net,ar}}$: net calorific value as received; $1 \text{ kcal} = 4.186 \text{ kJ}$.

Table 2
The parameters of central partition plate structure

Case	Baffle angles
1	Tilt to lean side 10°
2	0°
3	Tilt to rich side 3°

4.3. Optimization of operational conditions

The operational conditions of the burner with the optimal structure were optimized after its optimal structure was determined, based on the comprehensive analysis of the characteristics of flow field, rich-lean separation, combustion and NO_x emission characteristics of the burner. The effects of primary air velocity (v_1) and mass flow rate of pulverized coal (FM) on burner performance were investigated under the condition of the fixed particle diameter of pulverized coal and primary air temperature. Table 3 shows the parameters of each operational condition.

5. Simulation Results and Analysis

5.1. Combustion characteristics comparison between different coal types

Fig. 4 shows the numerical simulation results of combustion of coal with different volatile contents. When burning lean coal, the large temperature gradient occurred when $x = 3.5 \text{ m}$, i.e. 1.5 m away from the outlet, where it could be regarded as the pulverized coal ignition position. Whereas the high volatile coal was on fire when $x = 2 \text{ m}$, i.e. at the nozzle, indicating that the high volatile coal was easier to catch fire than the lean coal. The ignition position of the lean side of the high volatile pulverized coal is 1.3 m further away from the outlet than that of the rich side, and the ignition time difference between the two sides was not long. On the contrary, when burning lean coal, the ignition time difference between the two sides was longer, and their ignition positions were about 4.0 m apart. There was a tendency of gradual ignition from rich to lean side, and the maximum temperature was finally reached at a position of 7.0 m away from the nozzle. In addition, when burning lean coal, the ignition position was located in the recirculation zone on the rich side, which indicated that the stepped powder collecting flame stabilizer had played the role of hot flue gas backflow and step-by-step ignition of the rich and lean pulverized coal. The right half of Fig. 4 shows the scatter distribution of volatile release rate, in which the scattering points represent the release rate of pulverized coal volatiles on each line along the x -axis direction of the burner jet flow on the central horizontal plane. According to their distribution density, the average value represented by the ordinate at a certain distance from the nozzle on the central horizontal cross section can be estimated. The high volatile coal started to release volatiles at the position of 0.3 m away from the nozzle, and all volatiles were released at the position when $x = 4.5 \text{ m}$; whereas burning lean coal, volatiles started to release at a distance of 1 m away from the nozzle, and the release

Table 3
The parameters of the operational conditions

Case	Primary air temperature/ $^\circ\text{C}$	Primary air velocity (v_1)/ $\text{m} \cdot \text{s}^{-1}$	Mass flow rate of coal (FM)/ $\text{kg} \cdot \text{s}^{-1}$	Excess air coefficient
4	220	20	2.91	0.40
5		24.9	2.91	0.47
6		30	2.91	0.57
7		20	2.5	0.44
8		24.9	2.5	0.55
9		30	2.5	0.66

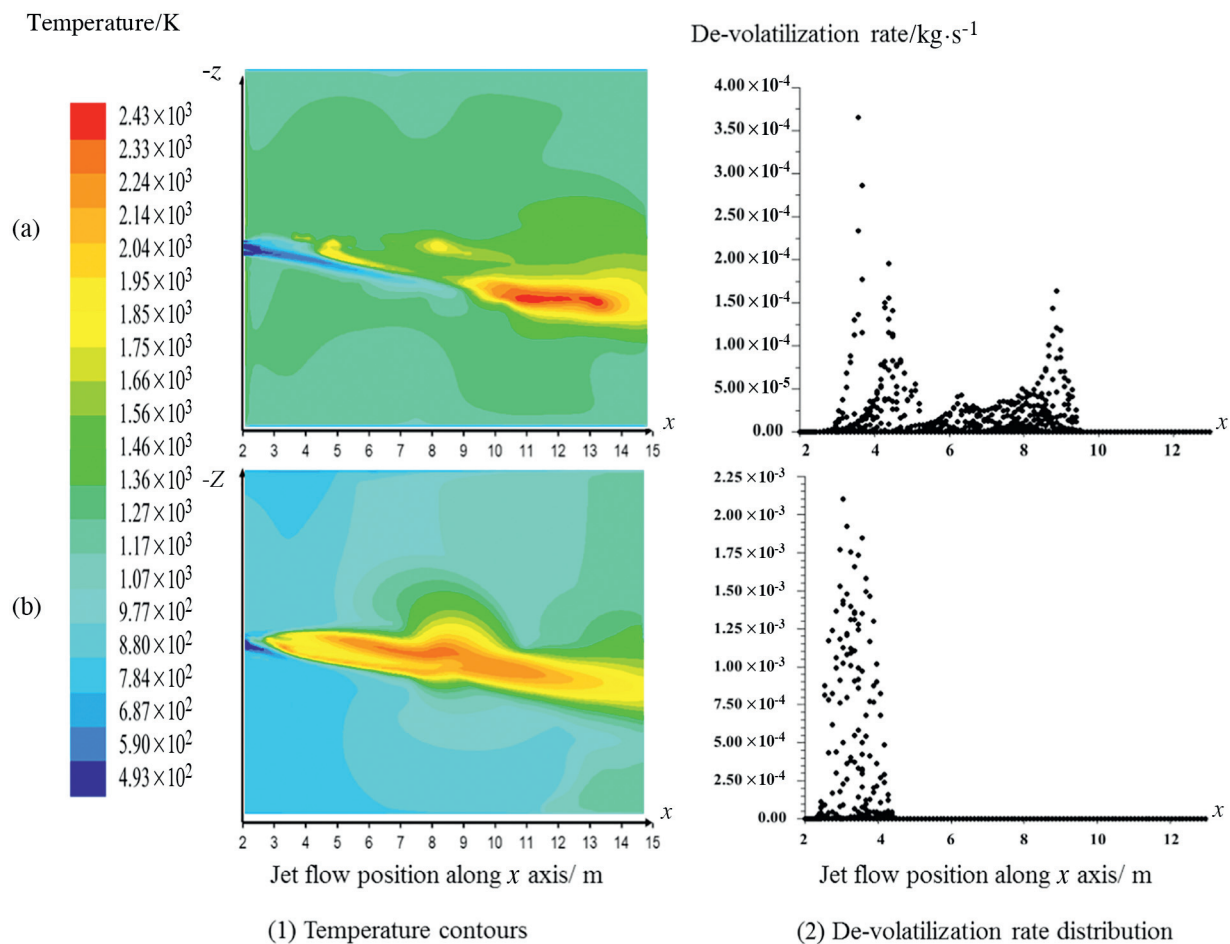


Fig. 4. Combustion characteristics of different coal: (a) lean coal, (b) high volatile coal.

continued until at a distance of 7.5 m away from the nozzle in a gradual release process, causing a phenomenon of step-by-step ignition.

5.2. Optimization of burner structure

The rich and lean separation characteristics of a horizontal rich and lean separation burner can be evaluated by the following parameters [21].

Rich/lean flow quantity ratio : $R_q = Q_n/Q_d$ (11)

Rich/lean concentration ratio : $R_c = C_n/C_d$ (12)

where, Q_n is the pulverized coal mass flow rate on the rich side, $m^3 \cdot s^{-1}$, Q_d is the pulverized coal mass flow rate on the lean side, $m^3 \cdot s^{-1}$, C_n is the pulverized coal concentration on the rich side, $kg \cdot (kg \text{ air})^{-1}$, and C_d is the pulverized coal concentration on the lean side, $kg \cdot (kg \text{ air})^{-1}$.

Noting that the closer to 1 R_q is, the better; and the bigger R_c is, the better.

Table 4 shows the results of the flow field characteristic with different baffle angles. The pressure drops in Case 1 were the smallest, as shown in Fig. 5(a). It was probably because that a large number of pulverized coal particles were concentrated in the flame holders with a sudden drop in sectional area, which greatly increased the resistance of the nozzle on the rich side. In Case 1, the partition plate tilted towards the lean side, and the sectional area on the rich side was larger than that in the other two cases (shown in Table 2). As a result, the total pressure drop from the inlet to the outlet of the burner was the minimum. Therefore, the average velocity on both sides in the Case 1 was smaller than

that in the other two cases. Fig. 5(b) shows the velocity vector distribution in the three cases. According to R_q and the ratio of mean velocity on the rich side (V_n) to the lean side (V_d), as shown in Table 4, despite low mean velocity, the difference in the mass flow rate and velocity between the rich and lean sides in Case 1 was the biggest, leading to the inclination of the jet flow (shown in Fig. 4), which was not acceptable. In Case 2, mass flow rate between the two sides R_q was 0.85, which was closer to 1 than the other two cases. Moreover, the rich/lean velocity ratio was 1.29, which was smaller than that in Case 1. Although the velocity ratio of rich/lean sides in Case 3 was 1.24, the lowest one, the R_q value of 0.71 was larger than that in Case 2. In conclusion, the flow characteristic of case 2 is more ideal.

In Case 2 the concentration ratio R_c reached 22.94 under the rated operational conditions, delivering the best separation effect. The values of R_c in Cases 1 and 3 were 16.28 and 15.42 respectively, far less than that in Case 2. Fig. 6 shows the contours of particle concentration in

Table 4
Flow field characteristic data

Case	Rich/lean side	Pressure drop/Pa	R_q	Average velocity/ $m \cdot s^{-1}$	Velocity ratio between rich/lean side(V_n/V_d)
1	Rich	598.85	1.30	39.28	1.39
	Lean			28.36	
2	Rich	740.01	0.85	45.24	1.29
	Lean			34.94	
3	Rich	768.51	0.71	47.63	1.24
	Lean			38.27	

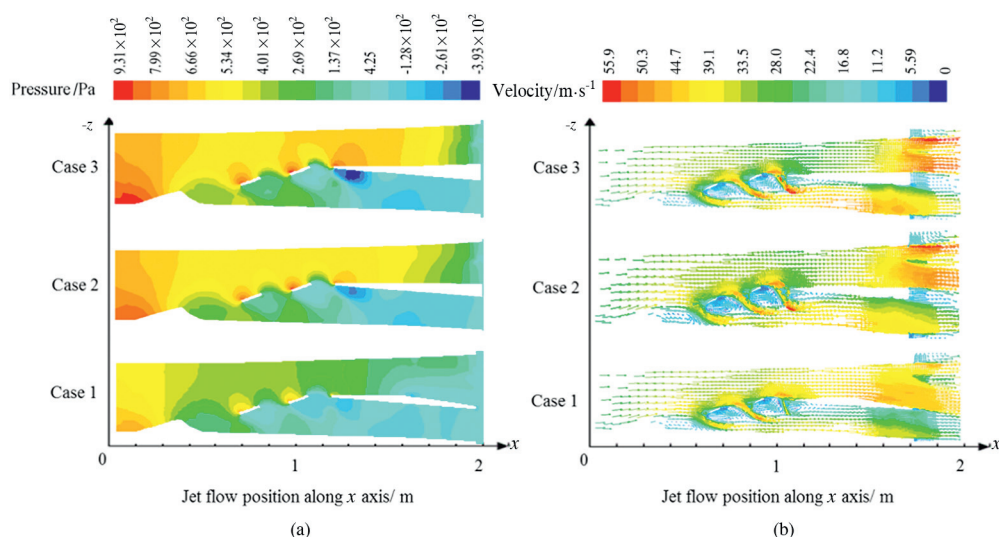


Fig. 5. Contours of (a) pressure (Pa) and (b) velocity vector ($\text{m} \cdot \text{s}^{-1}$).

the three cases. In Case 1, due to a large difference in speed between the rich and lean sides, the pulverized coal stream tilted obviously to the lean side and the pulverized coal stream was short and divergent. In Case 2, R_q was close to 1, with small deviation between the rich and lean sides, and pulverized coal particles formed a long and concentrated pulverized coal stream in the three-dimensional space. Thus in Case 2, the nozzle structure can reasonably organize the airflow to avoid segregation of pulverized coal. In Case 3, the velocity deviation between the two sides was the smallest and the pulverized coal jet flow was straighter than that in the other two cases. Whereas, since the mean velocity of both rich/lean sides in Case 3 was the biggest, the turbulence energy of it was the highest. Therefore, the rich coal air flow was disturbed, leading to divergent coal particle. In conclusion, among the three cases, the jet flow had stronger penetration and the pulverized coal stream had better stability in Case 2, which was conducive to providing reliable guarantee for efficient combustion and low nitrogen emission of burner burning in the boiler. Thus, case 2 was chosen as the optimized structure.

5.3. Optimization of burner operational conditions

The operational conditions of the burner with the optimal structure in Case 2 were optimized. Fig. 7 shows the simulation results of the parameters of rich and lean separation in Cases 4–9. With the increase of v_1 , R_q decreased, further away from 1. When mass flow rate (FM) was $2.91 \text{ kg} \cdot \text{s}^{-1}$, R_q was larger than that when FM was $2.5 \text{ kg} \cdot \text{s}^{-1}$, indicating that when the mass flow of pulverous coal was large, the air ratio between the rich and lean sides was closer to 1, which was more ideal. While, there was not big difference in the ratio R_q in different conditions. Fig. 7(b) shows the R_c results, in which R_c was lower when FM was $2.91 \text{ kg} \cdot \text{s}^{-1}$ than that when FM was $2.5 \text{ kg} \cdot \text{s}^{-1}$, indicating that the higher the mass flow of pulverized coal, the smaller the R_c . The R_c in Cases 5 and 8 were higher than that other cases. Therefore, when the primary air velocity v_1 was $24.9 \text{ m} \cdot \text{s}^{-1}$, it was most favorable for the rich and lean separation of the burner. With comprehensive consideration of R_q and R_c , the separation effect was the best in Case 8 ($v_1 = 24.9 \text{ m} \cdot \text{s}^{-1}$, $\text{FM} = 2.5 \text{ kg} \cdot \text{s}^{-1}$).

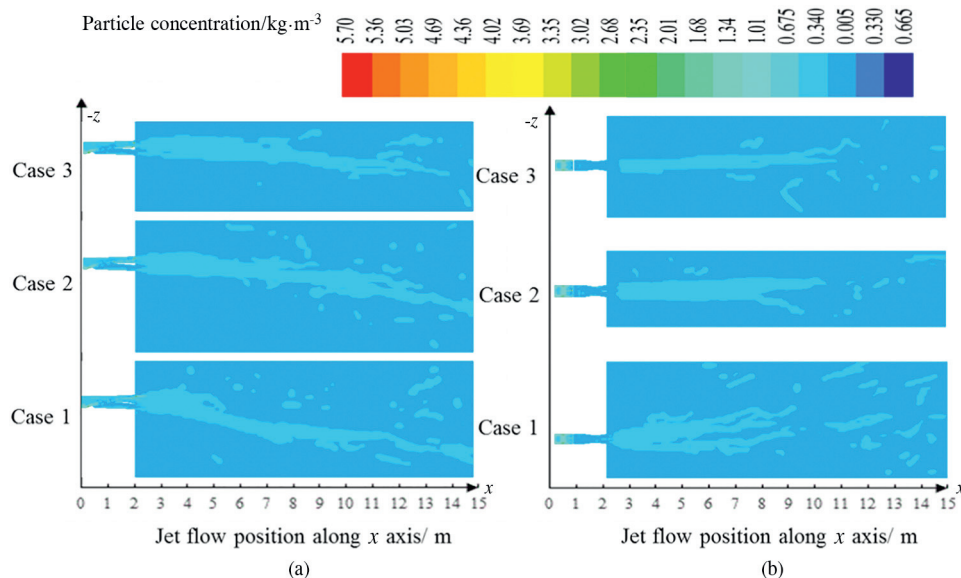


Fig. 6. Contours of particle mass concentration ($\text{kg} \cdot \text{m}^{-3}$): (a) central horizontal cross section; (b) central longitudinal cross section.

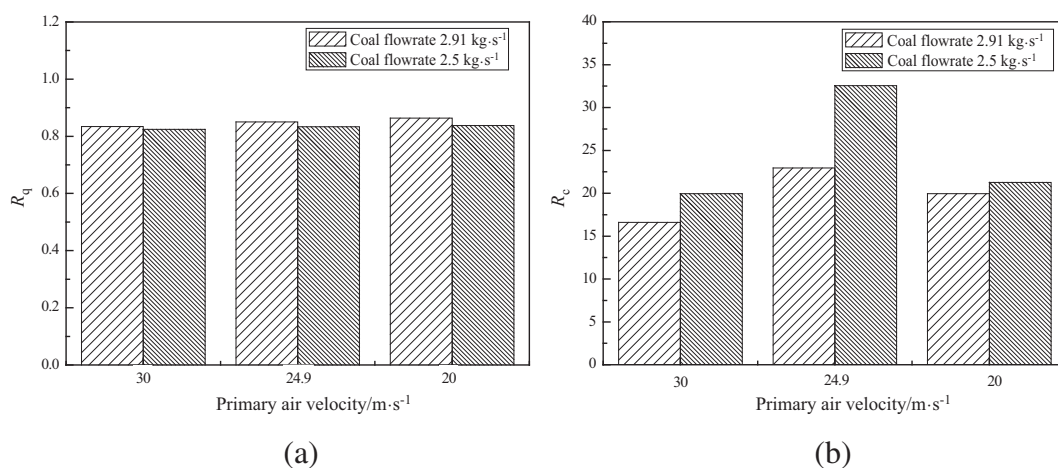


Fig. 7. Separation characteristics: (a) rich-lean air ratio R_q , (b) concentration ratio R_c .

Fig. 8 shows the distribution chart of mass concentration of pulverized coal particles on the central horizontal cross section and central longitudinal cross section of the virtual furnace outside the burner nozzle. The scattering points in the figure represent the pulverized coal concentration on each line along the x axis on the central

horizontal cross section (A) and the longitudinal cross section (B). The higher the occurrence frequency of the scattering points in the high concentration area, the higher the pulverized coal concentration in the area. When FM was 2.5 kg·s⁻¹, the high concentration in the horizontal cross section of the coal stream was maintained

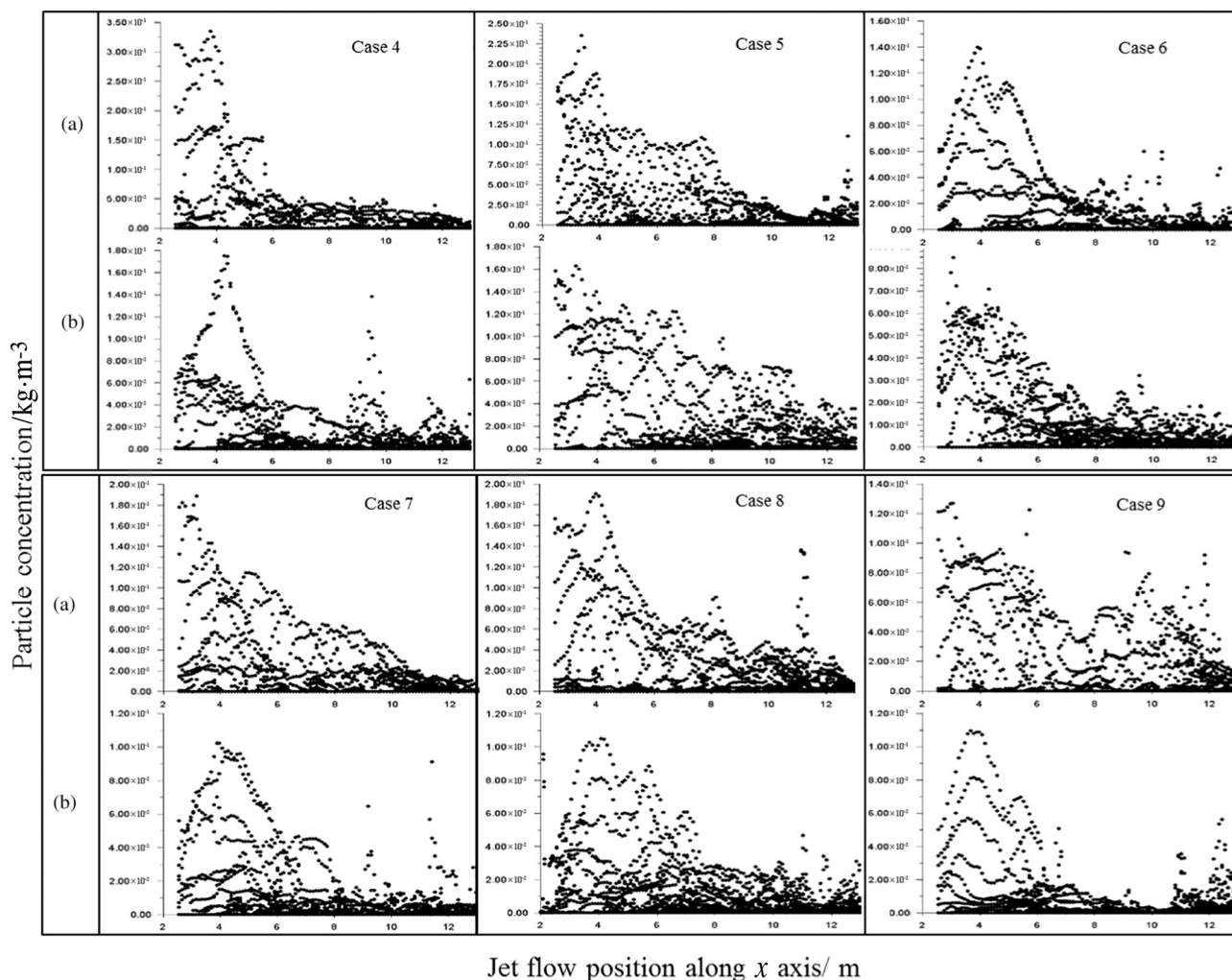


Fig. 8. Distribution of pulverized coal concentration on: (a) central horizontal cross section and (b) central vertical cross section.

further than that when FM was $2.91 \text{ kg} \cdot \text{s}^{-1}$. Moreover, the larger v_1 was, the easier the divergence of the pulverized coal stream. The maximum particle concentration and the average trend in the horizontal and vertical conditions of Cases 6 and 9 ($v_1 = 30 \text{ m} \cdot \text{s}^{-1}$) were smaller than those which v_1 was 20 or $24.9 \text{ m} \cdot \text{s}^{-1}$. When v_1 was $24.9 \text{ m} \cdot \text{s}^{-1}$ (Cases 5 and 8), the occurrence frequency of scattering points in high concentration area was higher than other cases. In Case 5, the occurrence frequency of scattering points on the vertical cross section in the high concentration zone was greater than that in Case 8. However, in Case 8, the high concentration on the horizontal cross section was maintained further away from the nozzle than that in Case 5.

The scattering points in Fig. 9 represent the volatile release rate or the mass fraction of CO_2 on each line along the x axis on the horizontal plane. The denser the scattering points are in the region with a large ordinate value, the larger its mean value is on the horizontal cross section. The volatile release and combustion rate basically showed two-stage property in all six cases. The first volatile release stage took place at the outlet of burner, but the second CO_2 release stage occurred in the main combustion area at the end of the jet flow. Therefore, it proved that the pyrolysis and combustion process took place in different stages, allowing for the decoupling combustion. In Case 4 and 7 ($v_1 = 20 \text{ m} \cdot \text{s}^{-1}$), both of volatiles release and

CO_2 concentration rapidly increased at the position of 1 m away from the burner outlet, indicating that volatiles release and combustion reaction occurred simultaneously with no obvious interval, which means there was no strongly decoupling combustion happened. The volatile release rates in Cases 6 and 9 were lower in the first stage, which was not conducive to the release of reducing gas. The reason could be that v_1 was too large, so the pulverized coal stream was easy to disperse and leads to low particle concentration which was not good for coal ignition. The volatile release rates in Cases 5 and 8 were high in the first stage and the maintained distance was longer than that in other cases, which provided favorable conditions for fully volatile release. As to the comparison between the two conditions, the volatile release rate in the early stage of Case 8 was higher than that in Case 5. In addition, the CO_2 concentration in Case 8 presented a more obvious two-stage separation, indicating that volatiles and char combustion staging in Case 8 were more obvious, and that the decoupling combustion was more sufficient.

The mean NO concentration at the virtual furnace outlet of different cases is shown in Fig. 10. In order to analyze the causes of NO release, NO concentration and temperature distribution of the furnace on the central horizontal cross section of each case were analyzed in Fig. 11. The temperature in Cases 4 and 7 was higher, because volatile release and combustion reaction registered high rate with violent reaction when

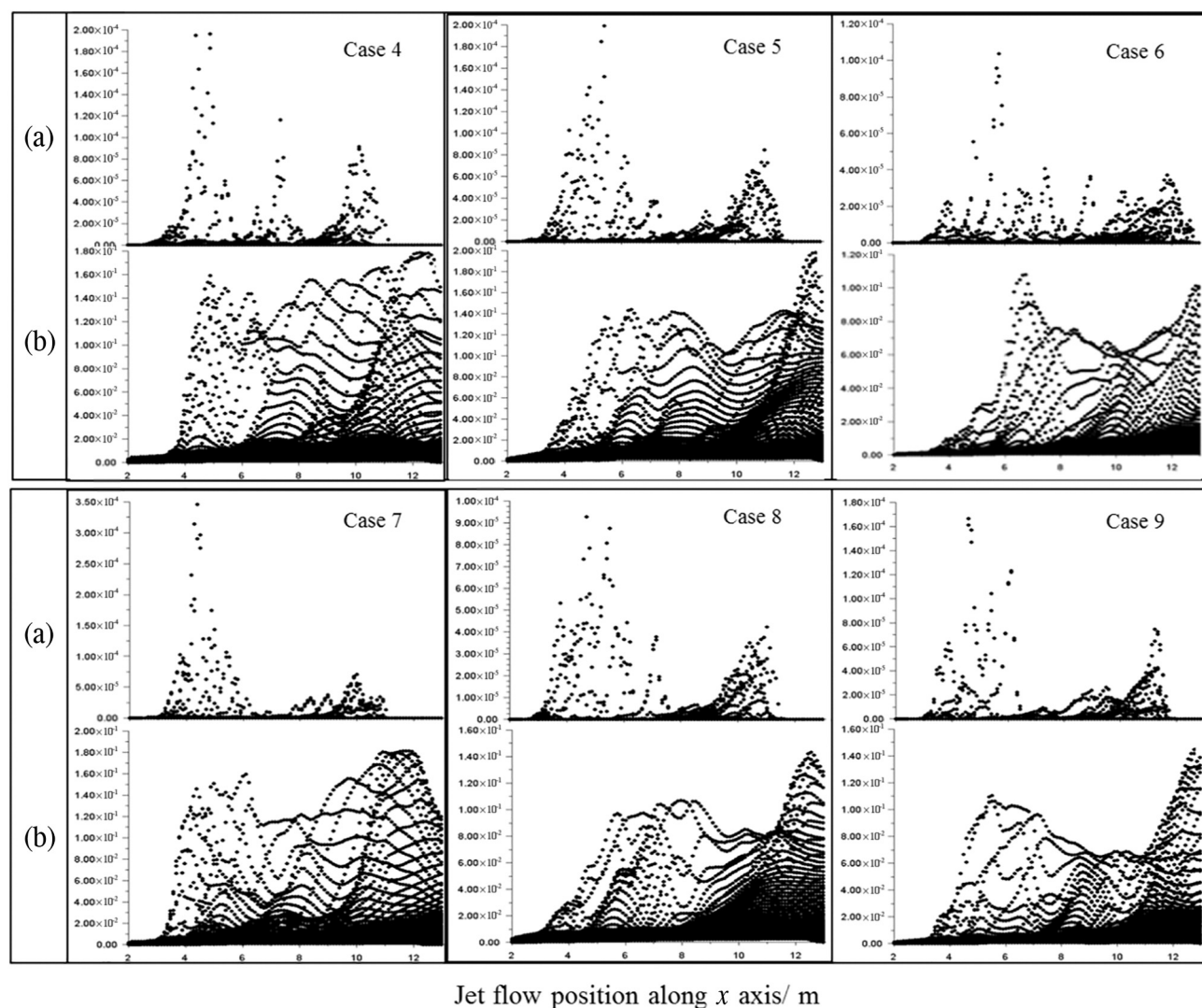


Fig. 9. Distribution of: (a) volatiles release rate ($\text{kg} \cdot \text{s}^{-1}$) and (b) mass fraction of CO_2 on central horizontal cross section.

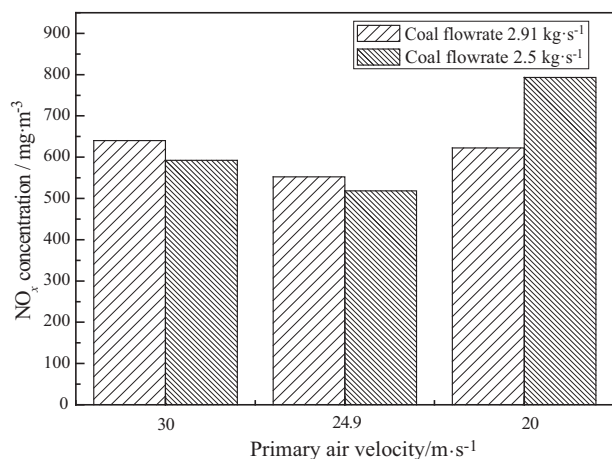


Fig. 10. Mean NO concentrations (mg·m⁻³) at outlet of virtual furnace.

v_1 was 20 m·s⁻¹ (Fig. 9), resulting in relatively high NO release concentration of 833.42 and 1062.53 mg·m⁻³ at the furnace outlet. In Case 6, due to dispersion of the coal particle (Fig. 8), volatile releases gradually,

and insufficient reducing atmosphere makes the NO generated fail to be effectively reduced. So, the NO concentration at the outlet was high at 857.44 mg·m⁻³. In the early stage of Case 9, the release rate of volatiles was slow, the release of NO was less, and NO diffused quickly because the pulverized coal bundle was short, forming a more uniform distribution. In addition, because of low char combustion rate and insufficient combustion, the final NO concentration was 793.15 mg·m⁻³. In Cases 5 and 8, the NO concentration and temperature were divided into two regions along the x axis. The first region featured the release and combustion of volatiles, in which the NO_x was reduced in the pulverized coal stream. Then, in the second high-temperature zone, that is, the burnout stage, part of NO_x was generated. As mentioned above, with increased concentration rate of pulverized coal, fully strengthened pyrolysis in the earlier stage, the coal pyrolysis was most strengthened in Cases 5 and 8 and concentration of pyrolysis gas in the initial stage of combustion increased. Meanwhile, pyrolysis gas with enough concentration fully contacted and reacted with the NO_x generated in the semi-coke layer, thus made full use of high reactivity pyrolysis products and high-temperature coke layer as a reductive agent to reduce NO_x, resulted in optimized nitrogen reduction effect. The mean values of NO concentration at the furnace outlet in the two cases were 739.62 and 694.26 mg·m⁻³ respectively. When compared with the design condition, the NO_x emission concentration in Case 8 reduced by 61.88%.

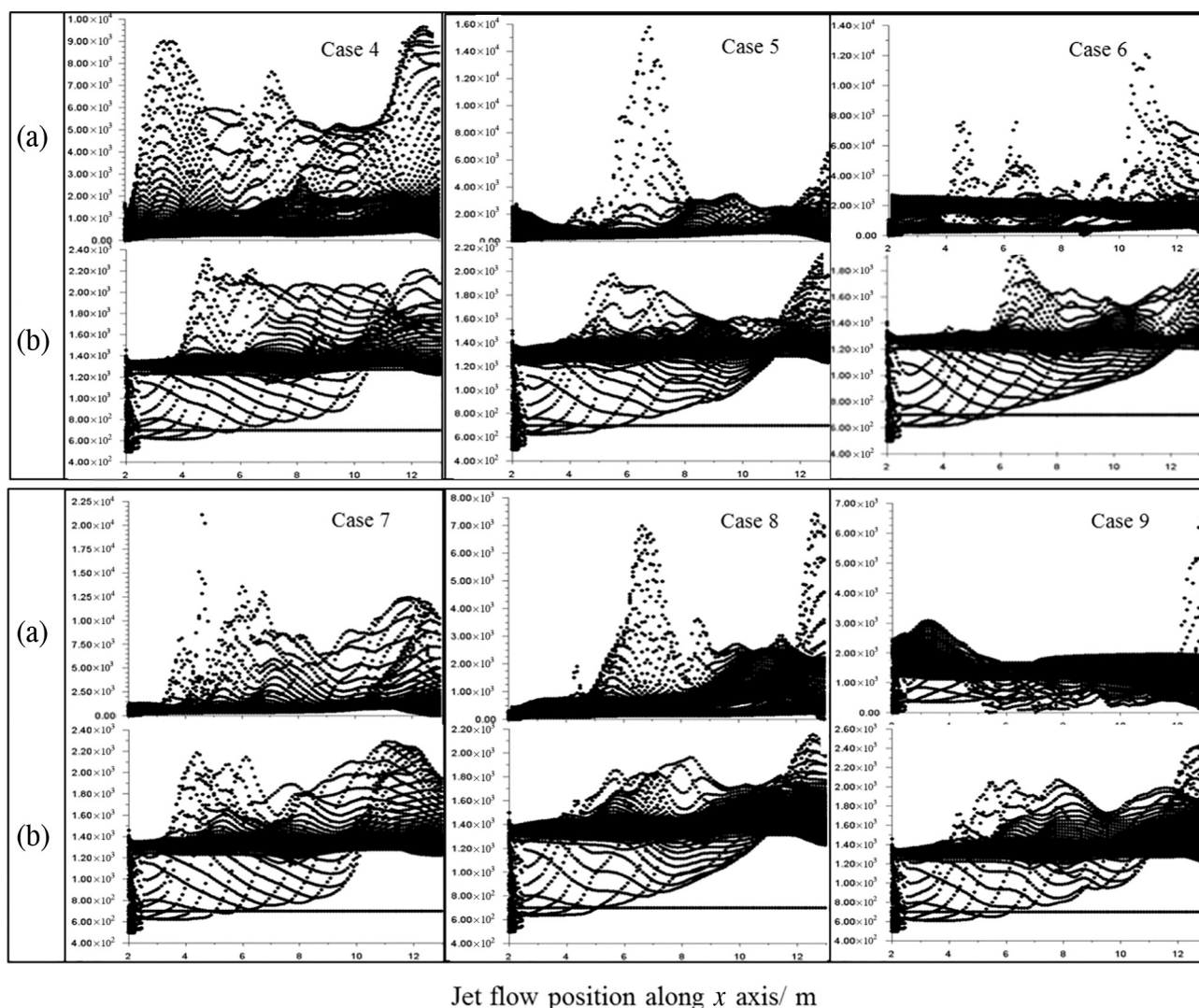


Fig. 11. Distribution curves of: A. NO concentration (mg·m⁻³) and B. temperature (K) on the central horizontal cross section.

Based on the above analysis, the primary air velocity was $24.9 \text{ m} \cdot \text{s}^{-1}$ and the mass flow rate of pulverized coal in the primary air was $2.5 \text{ kg} \cdot \text{s}^{-1}$ in Case 8, which was selected as the optimized operating parameters for lean coal decoupling burner.

6. Discussion

Numerical simulation in Fig. 4 showed that the low-speed recirculation zone generated at the high concentration zone of pulverized coal, and formed a stepwise ignition trend, which promoted the rapid ignition of lean coal. According to the two-stage property displayed in Fig. 9, the pyrolysis and combustion process took place in different stages, allowing for the decoupling combustion. As demonstrated in Figs. 10 and 11, to achieve the effect of fully reducing nitrogen by decoupling combustion, the optimized operation condition fully strengthened pyrolysis in the earlier stage, resulted in the high concentrated pyrolysis gas and long robust char stream were both utilized as reductive agent. Around the char stream, NO_x reduction reaction of homogeneous and heterogeneous phases is developed and the optimized nitrogen reduction effect achieved. Therefore, the NO_x emission concentration of which was 61.88% lower than that in the design condition.

Both the structural parameters and the aerodynamic parameters influence the characteristics of the flow field distribution, rich and lean separation and combustion, the combustion and the NO_x emission. However, the structural difference leading to more significant changes. The rich/lean side flow quantity ratio R_q of structural optimization changed from 1.30 to 0.71 (Table 4), yet operational parameter optimization changed only around 0.83 (Fig. 7(a)). As to NO_x emission, structural optimization caused it to change from 536.33 to $1821.23 \text{ mg} \cdot \text{m}^{-3}$ [22]. Nevertheless, that of operational parameter optimization changed from 670 to $1070 \text{ mg} \cdot \text{m}^{-3}$ (Fig. 10). Thus, the final flow and combustion results were mainly influenced by the structural parameters.

7. Conclusions

The stable combustion and low nitrogen principle of a decoupling combustion low NO_x burner were analyzed and discussed in this study based on the thermal numerical simulation. In addition, the structure and operating parameters of the burner were optimized in detail. The structure of this novel burner allows the pyrolysis and combustion process to take place in different stages. Therefore, it organizes stepwise ignition trend and strengthens the homogeneous and heterogeneous NO_x reduction, resulting in rapid ignition and low NO_x emission. The structure with an inclination of 0° showed good, rich and lean separation, and combustion performance, with its rich-lean air ratio being 0.85 and concentration ratio being 22.94, and there was an apparent decoupling combustion characteristic. The optimal operating parameters of the burner with selected structure was determined as the primary air velocity of $24.9 \text{ m} \cdot \text{s}^{-1}$ and the mass flow rate of pulverized coal of $2.5 \text{ kg} \cdot \text{s}^{-1}$. It was found that the structural parameters were the most important factor affecting the burner's ability. In conclusion, this research set the foundation for studying the complicated combustion system in the real power plant boilers.

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