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Determining the optimum coal concentration in a general tangential-fired furnace with rich-lean burners: From a bench-scale to a pilot-scale study

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HIGHLIGHTS

- The optimum coal concentration C_{opt} was proved in a bench-scale and a pilot-scale furnace.
- Effects of coal quality and burner layout method on C_{opt} were studied.
- C_{opt} generally changes with the coal quality as the empirical formula $C_{opt} = 1.19-0.15V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$.
- NO_x emissions can be much more efficiently controlled when coal concentration < C_{opt}.

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ABSTRACT

The mass ratio of pulverized coal and air (coal concentration, kg/kg) in fuel-rich streams is important in the design and operation of rich-lean burners, in which the optimum coal concentration (C_{opt}) that corresponds to the best combustion situation should be achieved. This study aims to establish a practical identification method to evaluate the C_{opt} of the different ranks of coal in rich-lean burners. A wide range of tests were conducted in a bench-scale down-fired furnace and a pilot-scale tangential-fired furnace with rich-lean burners. Temperature distribution, unburned carbon in ash, and NO_x emissions were measured, and the effects of coal quality aside from burner type and burner layout method were considered. Results show that the optimum coal concentration corresponds to the highest furnace temperature for each group of tests both in the bench-scale and pilot-scale furnaces. C_{opt} is significantly affected by coal quality even if a change from the use of a corner-tangential to a wall-tangential furnace lowers C_{opt}; however, the effect of a vertical rich-lean burner or a horizontal rich-lean burner on C_{opt} is negligible. The value of C_{opt} mainly decreases from 1.14 to 0.67 with a decrease in the volatile content from anthracite scale (<0.1) to lignite scale (>0.35). The empirical formula of $C_{opt} = 1.19-0.15V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$ is obtained to evaluate the optimum coal concentration of a general pulverized coal flame, and another formula, $C_{opt} = 1.18-0.17V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$, is especially derived for a tangential-fired furnace with a rich-lean burner. The optimum value obtained is also critical to NO_x emissions because when the coal concentration surpasses the value of C_{opt}, NO_x emissions can be much more efficiently controlled through reduction of air. The findings of this study can provide practical guidance for the design and operation of rich-lean burners to achieve high combustion efficiency and low NO_x emissions.

1. Introduction

Coal still accounts for about 70% of the total primary energy consumption in China, with coal-fired power plants producing 97% of the country's total thermal power capacity. In recent years, however, most power plants in China have been unable to burn the designed coal to control operation costs because of insufficient coal supply and increased coal prices [1,2]. Coal quality is usually of low grade and varies according to the ash content, volatile content, sulfur content, and heating value. Frequent fluctuations in coal

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Nomenclature

Latin alphabet

C	coal concentration, kg/kg
Carbon	fixed carbon content, %
D	equivalent diameter, m
G	mass flux of air, kg/s
H	specific heat capacity, kJ/kg
h	distance to the upper secondary air, m
M	moisture content, %
Q	heat value, MJ/kg
q	(ignition) heat, KJ/s
S	flame speed, m/s
T	temperature, °C
V	volatile content, %
Z	height, 1

Subscripts

ad	air dried
air	air
coal	coal
daf	dried and ash free
i	ignition
L	laminar
net	net
opt	optimum
R	relative
s	supply

Abbreviations

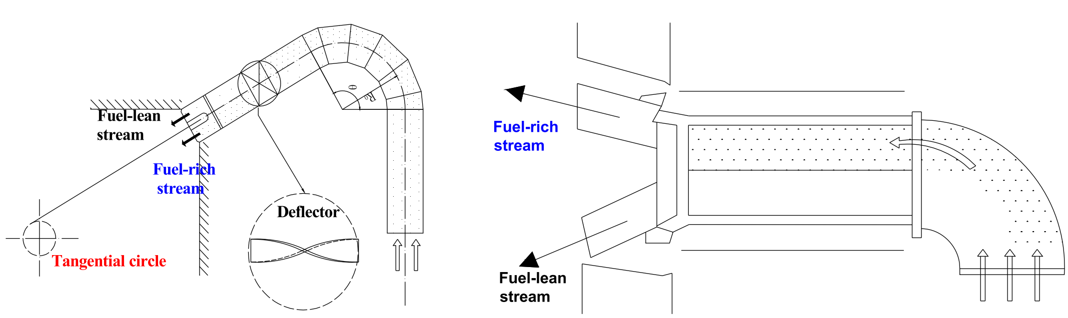
DFF	down-fired furnace
DTG	drop tube furnace
H-RL	horizontal rich-lean
JDN	Jin Dong Nan anthracite coal
LY	Long Yan anthracite coal
OFA	over fire air
PC	pulverized coal
SGT	Shi Ge Tai bituminous coal
SM	Shen Mu bituminous coal
TC	Tong Chuan lean coal
Temp.	temperature
TFF	tangential-fired furnace
V-RL	vertical rich-lean
YB	Yi Bin anthracite coal
ZX	Zou Xian bituminous coal

quality compromise operating safety, ignition, combustion efficiency, and pollutant emissions. The Chinese government has announced the latest national standard on NO_x emissions with an upper limit of 100 mg/m^3 for coal-fired power plants to encourage the use of low-NO_x combustion technologies, which is successfully used on furnaces burning bituminous coal with high volatile content. However, furnaces that burn low-quality coal with low volatile content are undesirable because low-NO_x burners induce an increase in unburned carbon and lower furnace efficiency even if NO_x emissions are reduced. A recent study by Hitachi Ltd. analyzed the relation between coal burnout and NO_x emissions in a fuel-rich coal flame and found that unburned carbon linearly increases with a decrease in NO_x emissions [3,4]. Consequently, maintaining high combustion efficiency in low-NO_x burners, especially with frequent changes in coal quality, is important in the design and operation of pulverized coal furnaces.

Currently, tangential-fired furnaces with direct flow burners and opposed-fired furnaces with swirling burners are commonly used in pulverized coal-fired power plants around the world; in China, however, tangential-fired furnaces are popular because tangential combustion can adapt to fluctuating coal quality and is efficient in air staging to control NO_x emissions [5]. In large-scale tangential-fired furnaces, rich-lean burners are usually employed, as shown in Fig. 1. The primary air of rich-lean burners is separated into fuel-rich and fuel-lean streams to create a condition of deep air staging, which not only reduces NO_x emissions but also improves the ignition and burnout of low-grade coal.

Generally, the overall mass ratio of pulverized coal and air (coal concentration, kg/kg) in the primary air of traditional burners is approximately 0.3–0.6; maintaining a stable flame for low-grade coal is difficult at such a low concentration [6]. However, Fig. 1 shows that after deep air staging, the coal concentration in a fuel-rich stream is generally over 0.6, and such a level can maintain a stable flame regardless of coal quality. The formation of a fuel-rich stream is important for the ignition of coal flame because a fuel-rich stream is adjacent to the high-temperature flame center (tangential circle, Fig. 1a) and is first ignited; in other words, a fuel-rich stream acts as a flame stabilizer [7].

Previous studies have focused on the ignition and combustion properties of fuel-rich streams with high coal concentrations. Taniguchi et al. [4] tested the laminar flame speed S_L of pulverized coal combustion in a drop tube furnace (DTF) and found that S_L increases to a maximum value and then slowly decreases with an increase in coal concentration; this result is similar to the measurement results in a Bunsen burner and a flat flame burner [8,9]. S_L achieves the maximum value in the range of 0.2 m/s to 0.4 m/s



(a) Horizontal rich-lean (H-RL) burner (b) Vertical rich-lean (V-RL) burner

Fig. 1. Two common schematic rich-lean burners.

when the coal concentration is changed, but the pulverized coal flame in industry furnaces is highly turbulent, and the practical turbulent flame speed S_t is 100 times that of S_L. Therefore, can the maximum flame speed or the best burning condition be obtained in a high-velocity, fuel-rich stream of a practical furnace, as shown in Fig. 1. In the past 20 years since the introduction of large-scale coal furnaces in China, investigations on the effect of coal concentration on the ignition of fuel-rich streams in practical furnaces have been conducted. For instance, Mitsubishi Heavy Industries Ltd. measured the ignition length of eight types of coal in a down-fired furnace (DFF) by modeling real turbulent combustion; the shortest ignition distance was found in the coal concentration range of 0.6–1.1, and it was mainly affected by coal quality [10]. In China, tests on the combustion of streams with high coal concentrations have been conducted in Huazhong University of Science and Technology and Xi'an Jiaotong University, and similar results have been obtained: an optimum coal concentration can achieve the shortest ignition distance and the highest furnace temperature [11,12]. The test results in a 300 MW furnace also indicated that an optimal primary air ratio can maintain the highest furnace temperature [13]. Furthermore, a recent work in the optical entrained flow reactor at Sandia National Laboratories proved that the best value of coal particle load for the shortest ignition distance can be achieved [14]. Moreover, some recent experimental and numerical works on the ignition and combustion of coal particle cluster also found that there should be an optimum coal particle number in the cluster for the shortest ignition delay time, and the existence of the optimum value should be related to the transition from heterogeneous ignition to homogeneous ignition [15–21]. The experimental results by Du et al. [15] indicated that homogenous ignition (ignition of volatile) occurs for a dense cluster while heterogeneous ignition (ignition of char) occurs for a dilute cloud, and the following modeling results by others also suggested that with the increasing in the coal particle concentration, the gas temperature distribution within the cluster tended to be uniform and homogeneous ignition was enhanced while heterogeneous ignition was retarded [18,20]. It should be noted that the optimum concentration was mainly found under the condition of homogenous ignition for dense cloud, while under the condition of heterogeneous ignition for dilute cloud this optimum value was not found.

Considering the high coal concentration in the fuel-rich stream of rich-lean burners, a concept called "optimum fuel concentration" (C_{opt}) should be put forward for fuel-rich streams: if burners are operated under this optimum condition, the combustion efficiency and ignition stability of pulverized coal furnaces can be significantly improved. This optimum value is considerably influenced by coal quality and, to some extent, by the combustion method involved. However, how to determine C_{opt} in the design and operation of rich-lean burners has not been quantitatively reported.

This study aims to establish a general and practical determining method to evaluate the C_{opt} of different ranks of coal in rich-lean burners. A wide range of tests are conducted in a bench-scale DFF and a 1 MW pilot-scale tangential-fired furnace (TFF) with rich-lean burners. Temperature distribution, unburned carbon in ash, and NO_x emissions are measured, and the effects of coal quality aside from burner type and burner layout method are considered.

2. Experimental setup

The experimental scheme of the DFF is shown in Fig. 2a. Coal feeding was controlled through a small, fluidized bed unit; primary air was preheated to 300 °C and had a velocity of 15 m/s to 25 m/s. The furnace was 168 mm in diameter and 800 mm in height. The primary air tube was 14 mm in diameter, and secondary air was injected through 16 holes on the circle at a distance of 83 mm from the center. The combustion-supporting premixed gas was injected through 8 holes at a distance of 47 mm from the center. Ten S-type thermocouples were arranged to measure the central temperature along with the height with an accuracy of ±1 °C [11]. C_{opt} in DFF experiments was defined as the coal concentration when the furnace temperature was the highest.

The experimental system of the 1 MW TFF is shown in Fig. 2b. The combustion section was 4200 mm in height, 770 mm in width, and 630 mm in depth. The burners with primary air (③), secondary air (②and④), and OFA (⑤, over fired air) were positioned at the corner or on the wall. The air preheater and the economizer were installed at the end of the furnace to decrease the exhausting temperature and to heat the primary air. The temperatures of the primary and secondary air were 80 °C–100 °C and 100 °C–170 °C, respectively, and air velocity was in the range of 20 m/s to 30 m/s.

The temperatures along the height were measured by a group of thermocouples. During treatment of the data, the relative height Z_R was defined as $Z_R = h/D$, in which h was the distance to the upper secondary air (②), and D is the equivalent diameter of the cross-section [22,23]. Aside from the temperature distribution, the unburned carbon in ash was also measured after isokinetic ash sampling, and NO_x emissions were recorded by DX-4000 FTIR analyzer (made by GASMET TECHNOLOGIES, Finland) with a measurement error of ±1 ppm.

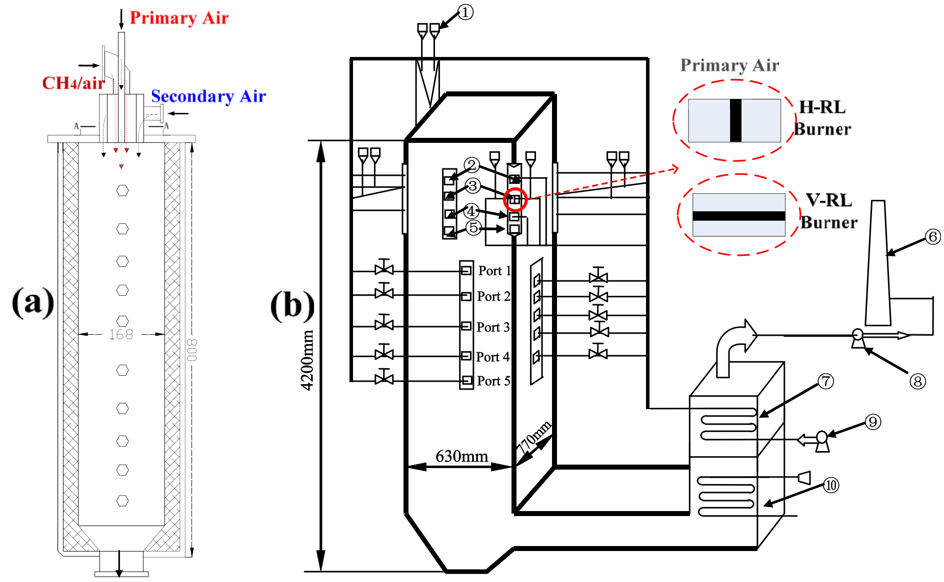
As shown in Fig. 3, the primary air was divided into fuel-rich and fuel-lean streams. The coal concentrations of the fuel-rich and fuel-lean streams for each burner were controlled by two screw feeders. In the experiments, the coal concentrations in the fuel-rich and fuel-lean streams changed, but the overall fuel concentration in primary air was approximately constant. The fuel characteristics and test conditions are listed in Table 1. Seven types of coal with volatile contents from 6.6% to 32.76% were used. V-RL burner and H-RL burner were compared, and the burner layout methods of corner tangential and wall tangential were also compared. In the experiments of tangential fired furnace, C_{opt} was defined as the coal concentration in fuel-rich stream when the furnace temperature was the highest or the unburned carbon in ash was the lowest.

3. Results and discussions

3.1. Verification and analysis of C_{opt} in the simplified bench-scale DFF

The existence of C_{opt} was first verified in the simplified bench-scale DFF. The temperature distributions along the furnace height under different coal concentration are listed in Table 2. For all the types of coal tested, the furnace temperature increases first and then decreases with an increase in the coal concentration, and a medium value under which the furnace temperature is the highest can be observed. The medium values are almost the same along the different heights for a special coal. Note that 13-LY anthracite is not shown in Table 2 because it failed to be sufficiently ignited in the facility; however, an iteration method based on the measured temperature data also showed the highest converted temperature at a coal concentration of 1.05 [11].

We recognize the medium value as C_{opt}, which is mainly within the range of 0.54–0.76, but it was affected by coal quality. The highest C_{opt} is for 12-ZX at 0.76, but the C_{opt} value is only 0.54 for 10-SM coal. The reason for this finding is the much lower heat value of 12-ZX (18.8 MJ/kg) than that of 10-SM (30.03 MJ/kg) even if the volatile content of 12-ZX coal is the highest. We propose a simplified analysis method based on ignition heat to explain why an optimum value was observed, and the ignition heat (q, kJ/s) needed is calculated as.



(a) Bench-scale DFF with single burner (b) 1MW pilot-scale TFF with rich/lean burners:

1-PC feeder; 2-Upper secondary air; 3-Primary air; 4-Lower secondary air; 5-OFA; 6-stack; 7-Air preheater; 8-Induced draft fan; 9-Forced draft fan; 10-Economizer

Fig. 2. The bench-scale and pilot-scale test facility.

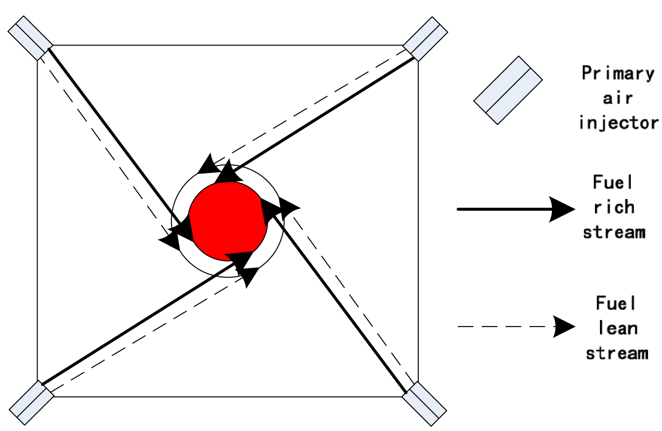


Fig. 3. The jet flow of fuel rich and fuel lean stream in the tangential combustion system with rich-lean burners.

$$q = G[H_{air}(T_i - T_{air}) + C \cdot H_{coal}(T_i - 20)] \quad (1)$$

where G is the mass flux of primary air, kg/s; H_{air} and H_{coal} are the specific heat capacities, kJ/kg; T_i is the ignition temperature, estimated as 840 °C for bituminous coal and 1000 °C for anthracite coal combustion under air condition according to the recent result by Riaza et al. [19]; T_{air} is the air temperature, °C; and C is the coal concentration, kg/kg.

In Eq. (1), the term $H_{air}(T_i - T_{air})$ is referring to the heat required by air from initial air temperature to the ignition temperature and the term $C \cdot H_{coal}(T_i - 20)$ is referring to the heat required by pulverized coal from room temperature to the ignition temperature. Because T_i is usually treated as a constant value for bituminous coal or anthracite coal as mentioned above, under the condition that G and T_{air} are constant, Eq. (1) can be converted to.

$$q = G \cdot H_{coal} \cdot (T_i - 20) \cdot C + G \cdot H_{air} \cdot (T_i - T_{air}) \\ = (G \cdot H_{coal} \cdot \Delta T_{coal}) \cdot C + (G \cdot H_{air} \cdot \Delta T_{air}) \quad (2)$$

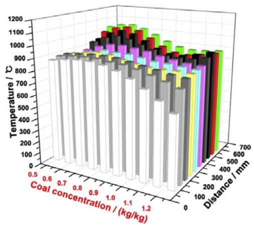
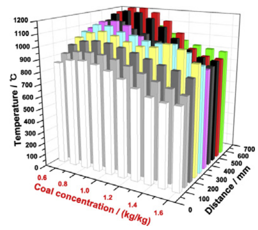
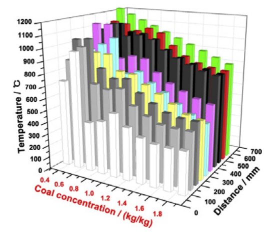
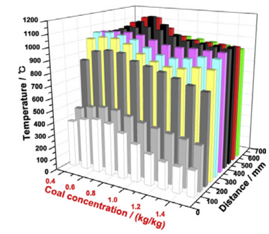
where ΔT_{coal} is the temperature difference between the ignition temperature and room temperature and ΔT_{air} is the temperature difference between ignition temperature and initial air temperature.

On the right side of Eq. (2), the terms in the brackets are constant, therefore, q linearly increases with C, as plotted in Fig. 4.

Table 1
Proximate analysis of coal and corresponding combustion methods.

No.	Coal name	$Q_{net,\ ad}$ MJ/kg	V_{daf} %	A_{ad} %	$Carbon_{ad}$ %	Burner type	Layout method	Furnace type
1-JDN	Jin Dong Nan anthracite coal	25.85	16.79	22.18	68.45	V-RL	Corner	1 MW tangentially combustion furnace
2-YB	Yi Bin anthracite coal	20.56	9.74	38.07	50.7	H-RL	Corner	
3-YB	Yi Bin anthracite coal	20.56	9.74	38.07	50.7	V-RL	Corner	
4-YB	Yi Bin anthracite coal	20.56	9.85	37.29	51.54	V-RL	Wall	
5-SM	Shen Mu bituminous coal	28.73	32.76	6.56	73.63	V-RL	Corner	
6-SM	Shen Mu bituminous coal	28.73	32.76	6.56	73.63	V-RL	Wall	
7-TC	Tong Chuan lean coal	20.06	22.41	33.32	52.55	V-RL	Corner	
8-TC	Tong Chuan lean coal	18.06	23.92	37.73	48.37	H-RL	Corner	
9-TC	Tong Chuan lean coal	20.46	22.1	35.75	49.38	Simplified down-fired furnace		
10-SM	Shen Mu bituminous coal	30.03	31.06	5.81	74.64			
11-SGT	Shi Ge Tai bituminous coal	22.71	37.7	18.22	57.45			
12-ZX	Zou Xian bituminous coal	18.80	40.3	25.47	59.74			
13-LY	Long Yan anthracite coal	23.33	6.6	24.08	64.82			

Table 2
Temperature profile and optimum coal concentration in bench-scale test.

Coal	9-TC	10-SM	11-SGT	12-ZX
Temp.				
C_{opt}	0.66	0.66	0.54	0.76

Under a low coal concentration, the heat supply q_s is higher than q ($q < q_s$), and the pulverized coal stream is ignited, but the furnace temperature is low because the coal concentration is low, and less heat is released. When the coal concentration increases to C_{opt}, the heat needed for ignition is equal to the heat supply ($q = q_s$) and thus results in the highest furnace temperature and heat release. If the coal concentration is higher than C_{opt}, $q > q_s$ and the heat supplied to ignite the coal stream is inadequate, the furnace temperature decreases.

In this bench-scale test, the heat supplied mainly came from surrounding CH_4 combustion, and we estimated that 80% of the heat released by CH_4 combustion was supplied to the pulverized coal stream. Plotting the heat supply in Fig. 4, we obtained the value of C_{opt} for bituminous coal at 0.67, which was close to the experimental results.

3.2. Results in the 1 MW pilot-scale tangential-fired furnace with rich-lean burners

3.2.1. Effect of coal concentration on the temperature along the furnace height

On the basis of the results in the bench-scale test, the optimum coal concentration was further investigated in a 1 MW pilot-scale tangential-fired furnace with rich-lean burners. The central temperature distribution along the furnace height under the conditions of different coal qualities and combustion methods is shown in Fig. 5. Because the fuel-rich stream plays a major role on the

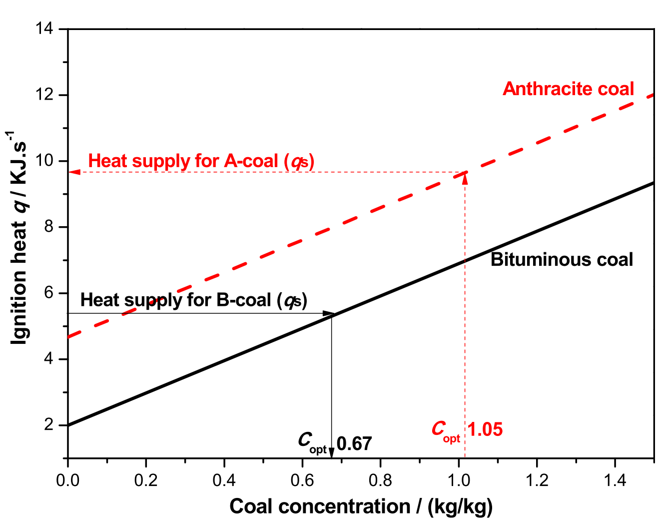


Fig. 4. The schematic diagram of the relation between ignition heat and coal concentration.

ignition of the overall pulverized coal stream in tangential-fired furnaces, the coal concentration used for the plotting in all the figures below is referring to the coal concentration in fuel-rich streams. As indicated by the shadow, an optimum coal concentration that corresponds to the highest furnace temperature for each group of tests can be observed, and this is regardless of coal quality or the combustion method used. However, the values of C_{opt} change when the coal quality or combustion method used changes.

Under the same combustion methods (V-RL burner and corner tangential combustion, Fig. 5a/c/e/g), the C_{opt} of 5-SM bituminous coal is around 0.664, but that of anthracite and lean coal is much higher. The values of C_{opt} of 1-JDN anthracite, 3-YB anthracite, and 7-TC lean coal are 0.957, 1.025, and 0.850, respectively, because anthracite and lean coal with low volatile and high ash contents are more difficult to ignite than bituminous coal.

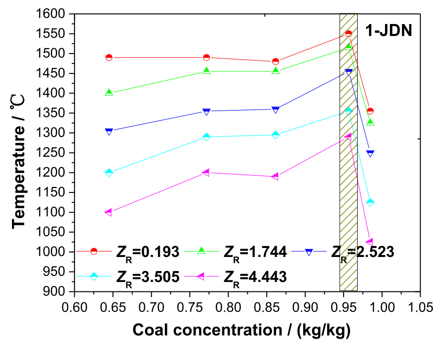
The comparison of YB anthracite in Fig. 5c and d shows that the C_{opt} under a wall tangential-fired furnace is only 0.83 lower than that of 1.025 under a corner tangential-fired furnace. The same result is also found for SM bituminous coal in Fig. 5e/f: C_{opt} is reduced from 0.664 to 0.607 when the corner tangential-fired furnace is changed to a wall tangential furnace.

The effect of burner type on C_{opt} is indistinctive. Whether for H-RL or V-RL burner, the C_{opt} values of YB anthracite coal and TC lean coal are about 1.026 (Fig. 5c/d) and 0.9 (Fig. 5g/h).

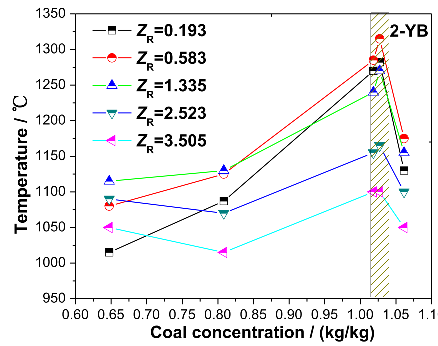
3.2.2. Effect of coal concentration on unburned carbon in ash

The unburned carbon content in ash is another important parameter to evaluate the status of ignition and burnout. Fig. 6 shows the effect of coal concentration on unburned carbon content. The value in Fig. 6 was the converted ratio of the real and average value in each group to compare the eight groups of tests in one figure.

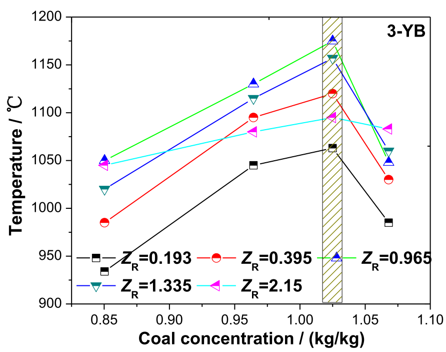
Comparison with Fig. 5 shows that an optimum value of coal concentration that corresponds to the lowest unburned carbon content in Fig. 6 can also be observed, and the value of C_{opt} agrees well with that in Fig. 5. The effects of coal quality, burner type, and layout method on unburned carbon agree with those on furnace temperature. Zhao et al. [21] proposed a transient group combustion model for pulverized coal particles, which believed that the ignition and burnout of coal particle cluster like fuel-rich stream should be ascribed to homogeneous (volatile) ignition. When the coal concentration is low, with the increasing in coal concentration, more volatile is released which is in favor of homogenous ignition and burnout of the coal particle cloud; however, when the coal concentration is higher than the optimum coal concentration, even if the homogenous ignition is enhanced, but it takes more time to preheat the densely populated coal particle cloud. This results in the existence of the optimum coal concentration in fuel-rich coal combustion.



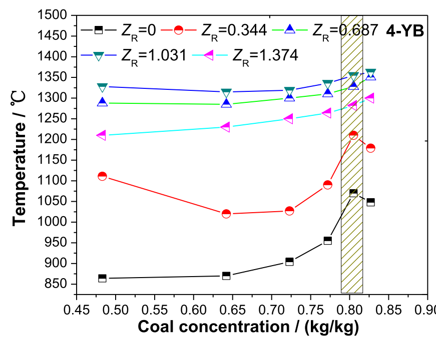
(a) 1-JDN, anthracite coal, V-RL burner, Corner tangential combustion



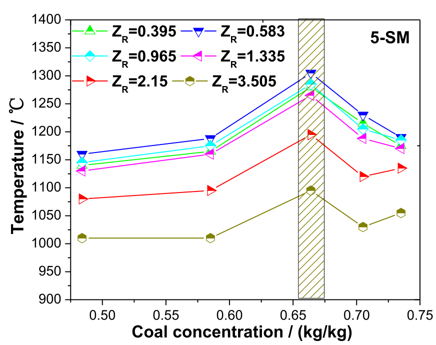
(b) 2-YB, anthracite coal, H-RL burner, Corner tangential combustion



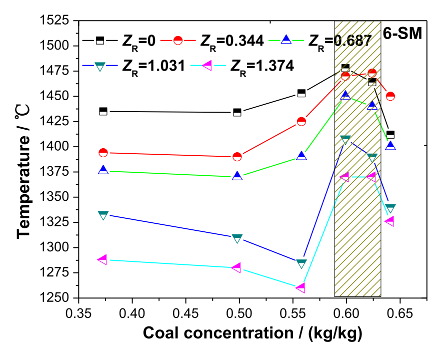
(c) 3-YB, anthracite coal, V-RL burner, Corner tangential combustion



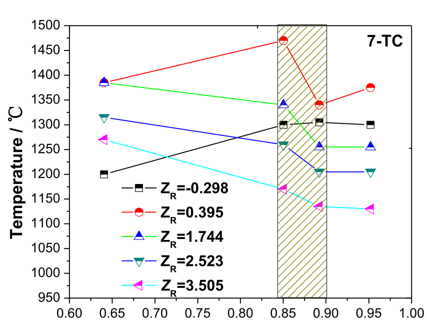
(d) 4-YB, anthracite coal, V-RL burner, Wall tangential combustion



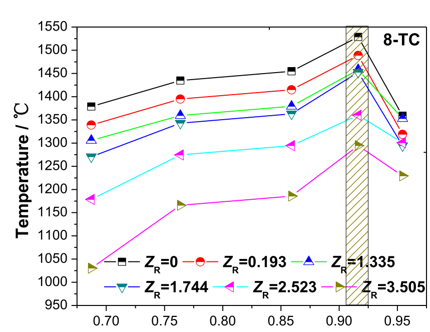
(e) 5-SM, bituminous coal, V-RL burner, Corner tangential combustion



(f) 6-SM, bituminous coal, V-RL burner, Wall tangential combustion



(g) 7-TC, lean coal, V-RL burner, Corner tangential combustion



(h) 8-TC, lean coal, H-RL burner, Corner tangential combustion

Fig. 5. Central temperature distributions along the height of pilot-scale furnace.

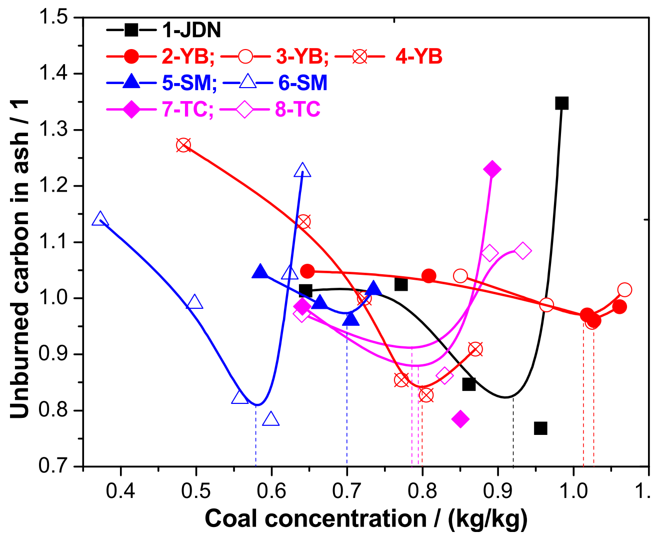


Fig. 6. Relation between coal concentration and unburned carbon content in ash.

3.2.3. Effect of coal concentration on NO_x emissions

The effect of coal concentration on NO_x emissions is shown in Fig. 7. Because the NO_x emission from different kinds of coal combustion varies greatly, in order to put all the plots of NO_x emission changing with coal concentration for different coal in one figure and make it comparable, the NO_x emission shown in Fig. 7 were also the converted relative ratio of the real and average value in each group test for a specific coal as the treat method of unburned carbon content in Fig. 6.

All the tests indicate that NO_x emissions decrease with an increase in coal concentration, and notably, a break point for each curve of Fig. 7 can be observed. When the coal concentration is higher than the value of this point, NO_x emissions rapidly decrease. If we compare the coal concentrations at these break points with the C_{opt} obtained from Figs. 6 and 7, we can interestingly find that the coal concentrations at the break points in the NO_x emission curves also coincide with C_{opt}. Consequently, above the optimum coal concentration C_{opt}, with the increasing in coal concentration, both the NO_x emission and the combustion efficiency decrease; however, below the optimum coal concentration C_{opt}, with the increasing in coal concentration, the NO_x emission decreases but the combustion efficiency is increases. This indicated that a best combustion condition with the highest combustion efficiency and low NO_x emission can be achieved at the coal concentration of C_{opt}.

The relation between NO_x emissions and coal concentration demonstrates that NO_x emission can be controlled much more efficiently by reduction of air, when the coal concentration is higher than C_{opt}. It is similar to the boundary value of the air equivalence ratio between the fuel-rich and fuel-lean conditions in gas combustion. As we are aware of, in case of an air ratio <1, reducing air can significantly control NO_x emissions. Moreover, when the coal concentration is higher than the optimum value, the unburned carbon increases significantly shown in Fig. 6, which also indicates that under this condition the gas phase contains much more reduction species like hydrocarbon and carbon monoxide, and these species are efficient to reducing NO to N_2 [4]. This result is important in the operation of low-NO_x rich-lean burners. If we control the coal concentration in fuel-rich streams to be slightly higher than C_{opt}, NO_x emissions can be significantly reduced.

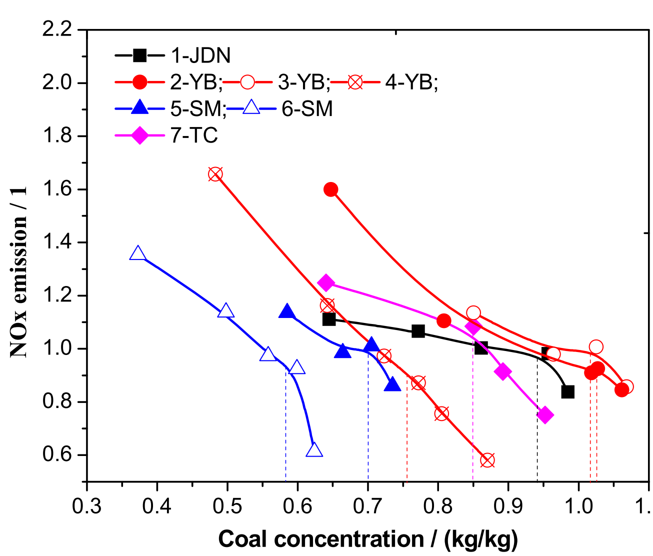


Fig. 7. Relation between coal concentration and NO_x emission.

3.3. Discussion and determination on C_{opt} in pulverized coal flame

3.3.1. Effect of burner type and layout on C_{opt}

The values of the optimum coal concentration for different types of burners and layouts are compared in Fig. 8. For corner tangential combustion (CT in Fig. 8), when we change the H-RL burner to V-RL burner, the C_{opt} for anthracite slightly changes. This result indicates that the type of burner used does not affect the ignition and burnout of pulverized coal streams. However, if corner tangential combustion is changed to wall tangential combustion (WT in Fig. 8), the values of C_{opt} are significantly reduced by 10% for bituminous coal and by 20% for anthracite, a result indicating that the layout method of burners is important to the combustion of pulverized coal streams. C_{opt} is reduced under wall tangential should be due to more heat received by the burner zone in a wall tangential furnace. Tan [24] compared the heat received by the burner of a wall tangential and a corner tangential furnace and found that the heat received by the burner zone in the former type is 1.5 times that in the latter type. This result means that pulverized coal streams are easier to ignite in a wall tangential furnace than in a corner tangential furnace at the same furnace load.

3.3.2. Effect of coal quality on C_{opt}

The comparison results in Fig. 8 show that the effect of coal quality on C_{opt} is significant. Especially in China, the coal quality in

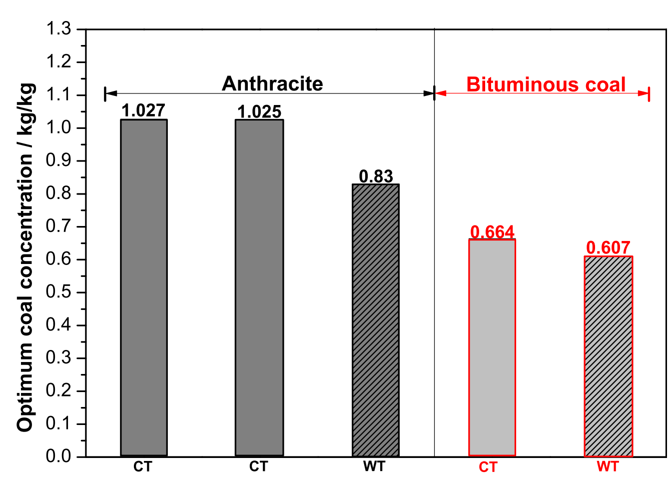


Fig. 8. Effect of coal quality and burner type on C_{opt}.

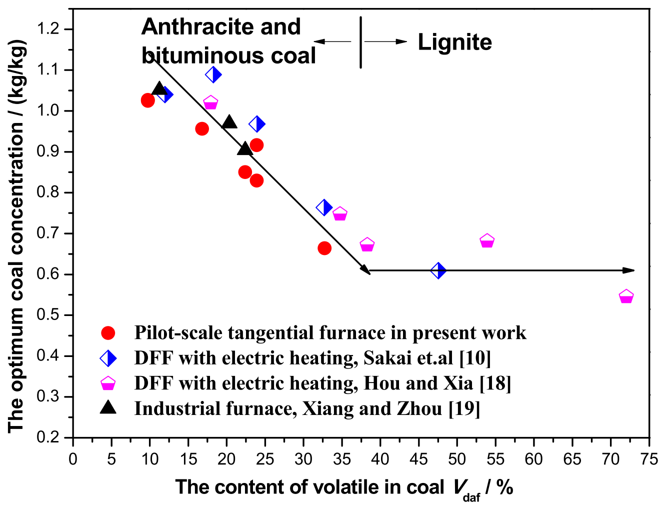


Fig. 9. Relation between volatile content and C_{opt}.

most power plants frequently fluctuates. Therefore, if we can determine the quantitative relation between coal quality and C_{opt}, operators can control furnaces at the highest combustion efficiency based on data on coal quality and through online monitoring of coal concentration and the use of adjustable concentrators.

In 1990s, Mitsubishi Heavy Industries Ltd. conducted a series of tests on the ignition of coal with low volatile content in a large down-fired furnace with the aim to promote the use of a pollution minimum burner in tangential-fired furnaces. Their results also showed that C_{opt} corresponds to the shortest ignition distance and decreases with an increase in volatile content [10]. Hou and Xia [25] observed the ignition of pulverized coal flow in a drop tube furnace, and they revealed that C_{opt} is mainly found for bituminous and lignite coal with a high volatile content. Moreover, Xiang and Xiong [26] obtained the values of C_{opt} in the range of 0.88–1.08 for bituminous coal, lean coal, and anthracite coal in a practical power plant and indicated that C_{opt} is mainly affected by the volatile content of coal; the effect of air temperature is negligible.

Because the volatile content of coal is generally regarded as the simplest and the most important parameter that describes coal ignition, the relation between C_{opt} and volatile content is plotted in Fig. 9 with the use of data in both present and previous works. The figure shows that the value of C_{opt} mainly decreases from 1.14 to 0.67 with a decrease in volatile content from anthracite scale (<0.1) to lignite scale (>0.35) and is relatively stable at a range of 0.55–0.7 for lignite coal. The fitting line in Fig. 9 indicates that the maximum error between the fitting and experimental data is below 0.1, so this simple method based on volatile content is valid to estimate C_{opt} when the coal quality changes.

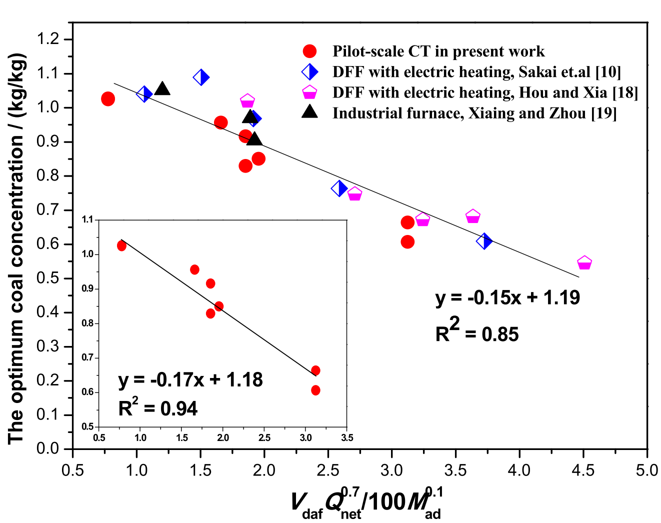


Fig. 10. Relation between coal quality and C_{opt}.

3.3.3. *Empirical formula of C_{opt} for the design and operation of a rich-lean burner*

Aside from volatile content, the ash and moisture contents that affect the heat value of coal should also affect the determination of C_{opt}, especially for anthracite and lean coal with a low volatile content or high ash content. The collected experimental data show that the optimum coal concentration generally decreases with increasing in moisture content of coal and increases with the increasing in the heat value of coal, but neither the fitting between C_{opt} and moisture content nor the fitting between C_{opt} and heat value is as good as that between C_{opt} and volatile content, and the optimum coal concentration fluctuates in a large range of 0.55–1.1 kg/kg. However, considering the moisture content and heat value in the fitting formula between C_{opt} and coal quality parameters, the fitting formula can agree much better with the experimental data. Further plotting of the relation between C_{opt} and $V_{daf}Q_{net}^{0.7}/M_{ad}^{0.1}$ is shown in Fig. 10, which indicates that C_{opt} linearly decreases with an increase in $V_{daf}Q_{net}^{0.7}/M_{ad}^{0.1}$ in a wide range. The relation is represented by the formula $C_{opt} = 1.19 - 0.15V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$ with a maximum error under 0.1, where, V_{daf} is the volatile content, %; Q_{net} is the heat value, MJ/kg; M_{ad} is the moisture content, %.

Moreover, the present data from the pilot-scale furnace are replotted in Fig. 10 because the combustion process in the present 1 MW pilot-scale furnace is comparable to that in a practical furnace. A new formula, $C_{opt} = 1.18 - 0.17V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$, is obtained with a maximum error under 0.05. This empirical formula can best be applied for the optimal design and operation of rich-lean burners in tangential-fired furnaces.

4. Conclusions

(1) An optimum coal concentration that corresponds to the highest furnace temperature for each group of tests can be observed in both bench-scale and pilot-scale furnaces. C_{opt} is significantly affected by coal quality even if a change from a corner-tangential to a wall-tangential furnace lowers C_{opt}; the effect of a vertical rich-lean burner or a horizontal rich-lean burner on C_{opt} is negligible.
(2) The value of C_{opt} mainly decreases from 1.14 to 0.67 with a decrease in the volatile content of coal from anthracite scale (<0.1) to lignite scale (>0.35). The empirical formula of $C_{opt} = 1.19 - 0.15V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$ is obtained to evaluate the optimum coal concentration of a general pulverized coal flame, and another formula, $C_{opt} = 1.18 - 0.17V_{daf}Q_{net}^{0.7}/100M_{ad}^{0.1}$, can best be applied to tangential-fired furnaces with rich-lean burners.
(3) The optimum coal concentration is also critical to NO_x emissions because when the coal concentration surpasses the C_{opt}, NO_x emissions can be controlled much more efficiently through reduction of air. The results presented in this study can provide practical guidance for the design and operation of rich-lean burners to achieve high combustion efficiency and low NO_x emissions.

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