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Burning low volatile fuel in tangentially fired furnaces with fuel rich/lean burners

Xiaolin Wei [a,*], Tongmo Xu [b], Shien Hui [b]

[a] *Institute of Mechanics, Chinese Academy of Sciences, Bei Si Huan Xi Lu. 15, Beijing 100080, PR China*
[b] *Department of Thermal Engineering, Xi'an Jiaotong University, Xian Ning Xi Lu. 28, Shaanxi 710049, PR China*

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Abstract

Pulverized coal combustion in tangentially fired furnaces with fuel rich/lean burners was investigated for three low volatile coals. The burners were operated under the conditions with varied value N_d, which means the ratio of coal concentration of the fuel rich stream to that of the fuel lean stream. The wall temperature distributions in various positions were measured and analyzed. The carbon content in the char and NO_x emission were detected under various conditions. The new burners with fuel rich/lean streams were utilized in a thermal power station to burn low volatile coal. The results show that the N_d value has significant influences on the distributions of temperature and char burnout. There exists an optimal N_d value under which the carbon content in the char and the NO_x emission is relatively low. The coal ignition and NO_x emission in the utilized power station are improved after retrofitting the burners.

Keywords: Low volatile coal; Combustion; Fuel rich/lean burner; NO_x emission

1. Introduction

Large quantities of low volatile coal are utilized in power plants in China. Because of more and more fluctuation of electricity consumption, the boilers are frequently required to operate under low load conditions. Therefore, serious problems have arisen, such as poor stability of the flame, low combustion efficiency and environmental pollution [1].

Many researchers have reported the air staging or combined air and fuel staging (reburning) as a means to reduce NO_x emissions [2–8]. Some new burners have been developed in which the

* Corresponding author. Tel.: +86-10-62545533x3052; fax: +86-10-62561284.
E-mail address: xlwei@imech.ac.cn (X. Wei).

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primary air is separated into fuel rich/lean streams to provide an air staging condition [9–11]. Besides reducing NO_x emission, this staged combustion can also improve the ignition and burnout of low volatile coal [10,11].

In the primary air of a pulverized coal (PC) burner, the fuel/air mass ratio normally is about 0.3–0.6 kg(coal)/kg(air). However, results indicate that the optimum ratio for low volatile coals may be 0.6–1.4 kg(coal)/kg(air) to achieve stable ignition [12–14]. Because the fuel/air mass ratio in the primary air for traditional pulverized fuel burners cannot reach this high level, pulverized fuel concentrators have been utilized in burners to separate the primary air into two fuel rich/lean streams, and then they go to two separate burner nozzles [15–19]. Both of the nozzles have a synergistic effect on coal ignition because when the coal rich stream enters the furnace, it is firstly ignited and then the coal lean stream is ignited by it. Owing to the lower oxygen content in the high concentration PC region and the lower gas temperature in the low concentration region, NO_x emission can be controlled at a low level.

Up to now, although the tests of the single burner have been conducted, few experimental results were reported about burners with coal rich/lean streams utilized in tangentially fired furnaces. The object of this paper is to investigate burning low volatile coals in PC furnaces with coal rich/lean burners.

2. Test facility

Fig. 1 is the scheme of the test facility for a 1 MW (heat input power) PC combustor. The tangentially fired furnace is 4.2 m in height, 0.77 m in width and 0.63 m in depth. One group of PC

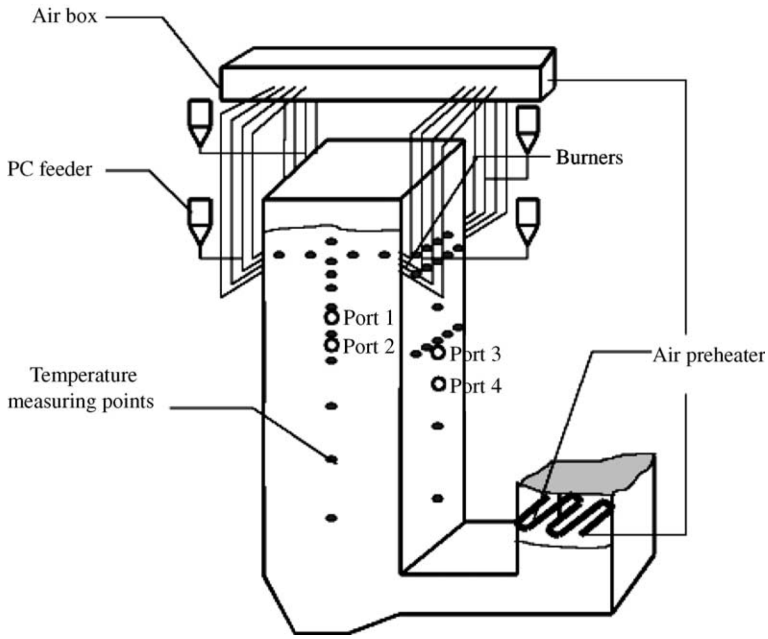

Fig. 1. The scheme of the test facility of tangentially fired furnace.

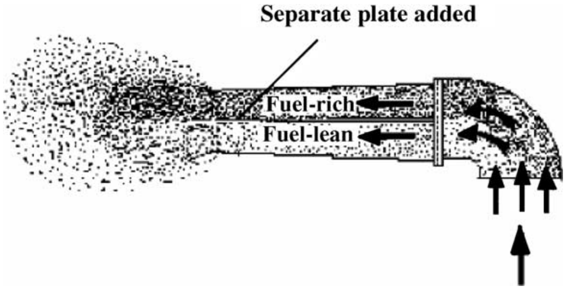

Fig. 2. The primary air separated into coal rich/lean streams.

burners is included, two upper and one lower secondary, as well as one primary, air nozzles. The primary air is separated into two streams by a plate added in the PC pipe (see Fig. 2).

One fluidized bed feeder is installed in each corner, which feeds two PC streams into the primary air separately, one for a coal rich stream and another for a coal lean stream. The fluidized bed feeder has been calibrated using the measuring weight method for various operating conditions, and the PC feeding rate has an accuracy of ±5% of the measured value. So, the coal feeding rates of the various nozzles can be quantitatively adjusted. In addition, an economizer and air preheater are installed in the flue, which may heat water and air as well as reduce the flue gas temperature.

The temperature was measured by platinum-rhodium thermocouples immersed in the wall. NO_x and RO_2 ($= CO_2 + SO_2$) were analyzed from sampling the flue gas in the exit of the furnace.

Tests were conducted for two low volatile coals (No. 1–No. 2), and coal No. 3 was utilized in a thermal power station. The content of ash in the coals is also high (22–43%). Table 1 shows the composition of the three coals. During the tests, the average PC concentration of the coal rich and

Table 1
The properties of coals

Chemical analysis	Coal No. 1	Coal No. 2	Coal No. 3
Moisture (*as received*)			10.29
Proximate analysis (*wt.%, air-dried basis*)			
Moisture	0.86	0.51	1.06
Volatile	12.92	14.83	13.68
Fixed carbon	64.04	51.34	42.23
Ash	22.18	33.32	43.03
Volatile (*wt.%, daf basis*)	16.79	22.41	24.47
Ultimate analysis (*wt.%, air-dried basis*)[a]			
Carbon	68.45	52.55	43.09
Hydrogen	3.53	2.94	3.11
Nitrogen	0.92	0.48	0.90
Sulphur	0.96	2.79	0.97
Oxygen (by diff.)	3.10	7.41	7.84
LHV (*MJ/kg, air-dried basis*)	25.85	20.06	18.16

[a] Data of ultimate analysis for coal No. 3 are estimated.

coal lean streams are maintained constant. Through changing the PC feeding rates, the PC concentrations of the two nozzles are changed separately. N_d is the ratio of the coal concentration of the fuel rich stream to that of the fuel lean one.

3. Experimental results

3.1. Furnace temperature

When burning low volatile and high ash content coals in the power station, the combustion stability becomes worse, especially under start up and low load conditions. In addition, a low combustion temperature also reduces the burnout of char and increases CO emission. On the other hand, if the furnace temperature is designed to be too high, NO_x emission and ash slag will increase. Therefore, this paper will investigate the burners with fuel rich/lean streams that not only can improve the ignition and burnout of low volatile coal but also may reduce NO_x emission.

Wall temperatures were measured through the thermocouples immersed in the inner wall of the test furnace. Figs. 3 and 4 indicate the wall temperature along the height (in the rear wall) for two coals. From the height of the primary air nozzle ($z = 0$), the temperature quickly increases with increasing the height z. When the height attains a certain location ($z = 0.670$ m), the temperature is a maximum and then slowly declines. The temperature level for coal No. 2 is lower than that for coal No. 1, and the flame temperature of coal No. 2 reduces more quickly along the height. Compared with coal No. 2, coal No. 1 has lower volatile matter and higher heating value. Therefore, the char burnout of coal No. 1 will need a longer time to finish, and the higher combustion temperature may be maintained for a relatively long time along the furnace height.

From these results, we can see that the ratio N_d greatly affects the flame temperature level. For coal No. 1, increasing the ratio N_d from 1.29 to 4.0 increases the flame temperature, but with increasing N_d from 4.0 to 6.0, the temperature reduces. Obviously, if N_d increases from 1 to ∞ (infinite), the temperature will not increase continuously because the mixing of air and PC

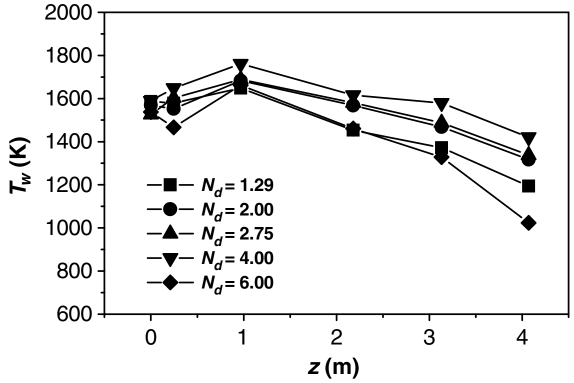

Fig. 3. The wall temperature distribution along the height for coal No. 1.

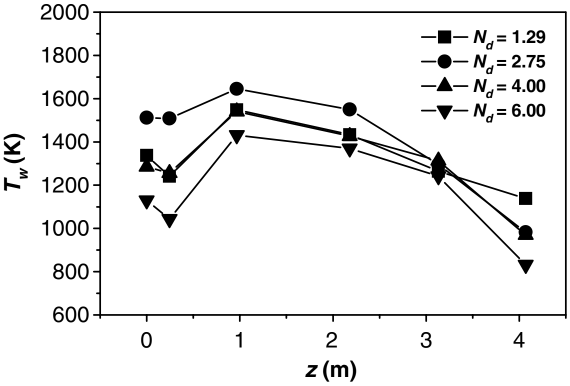

Fig. 4. The wall temperature distribution along the height for coal No. 2.

between the two nozzles may become too bad to support ignition. For coal No. 2, increasing N_d from 1.29 to 2.75 increases the temperature, and with increasing N_d from 2.75 to 6.0, it decreases. Obviously, the results indicate that the furnace temperature attains a maximum for a certain ratio N_d. We define this ratio as the optimal $N_{d,\mathrm{opt}}$ [16]. $N_{d,\mathrm{opt}}$ depends on the properties of the coal. For coal No. 1, $N_{d,\mathrm{opt}} = 4.0$, and the corresponding coal concentration is 0.9566 kg(coal)/kg(air) for the coal rich stream and 0.2391 kg(coal)/kg(air) for the coal lean stream. For coal No. 2, $N_{d,\mathrm{opt}} = 2.75$, and the corresponding coal concentration is 0.8504 kg(coal)/kg(air) for the coal rich stream and 0.3092 kg(coal)/kg(air) for the coal lean stream.

According to the single burner tests [14], the optimal PC concentration is 0.66 kg(coal)/kg(air) for coal No. 2. Therefore, the optimal coal concentration for PC combustion with coal rich/lean streams is higher than that for the single PC burner. The reasons for this phenomenon are complex, but one factor is the interaction of the coal rich/lean streams. When the PC streams enter the furnace, the air in the fuel lean stream may be mixed into the fuel rich stream, and this causes a reduction in the coal concentration of the latter.

3.2. Char burnout

During the tests, char was sampled from four positions at the furnace (see Fig. 1). The carbon content in the char is shown in Fig. 5 for coal No. 1 under various conditions (see Table 2). Because the sampling location is close to the burner zone, the carbon content in the char is relatively large and different in various positions. It is clearly shown that char burnout attains the best value under the optimum condition $N_{d,\mathrm{opt}} = 4.0$.

Fig. 6 indicates the carbon content in the char sampled from port. 2 under various ratios N_d for the two coals. The char burnout is improved with increasing the ratio N_d, but then with continuing to increase the ratio N_d, the char burnout becomes worse. The carbon content in the char attains the minimum under the condition with the ratio $N_{d,\mathrm{opt}}$. Obviously, this should be attributed to coal ignition improvement and temperature level enhancement through utilizing the fuel rich/lean burners in the PC furnace.

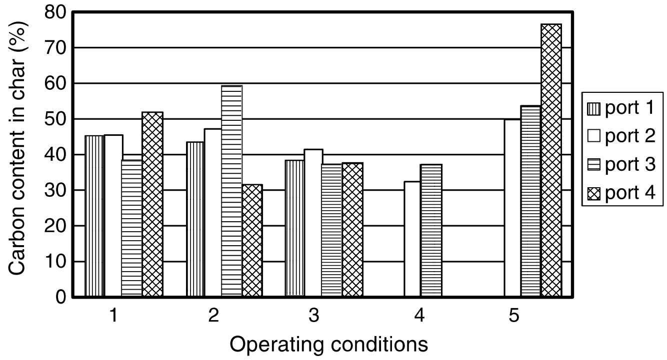

Fig. 5. Carbon content in char under various conditions for coal No. 1.

Table 2
Operating conditions for coal No. 1

No.	1	2	3	4	5
N_d	1.29	2.00	2.75	4.00	6.00

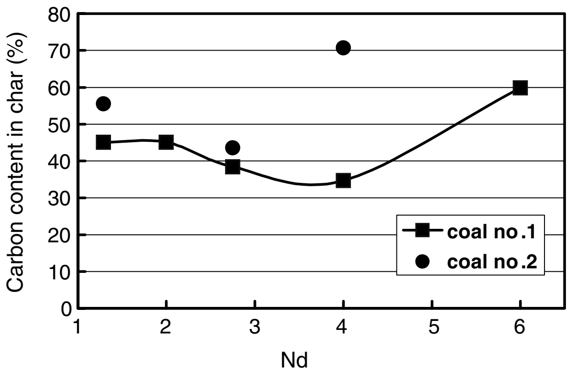

Fig. 6. Carbon content in char sampled from port. 2 under various ratios N_d.

3.3. NO_x emission

Results of the NO_x emission indicate the linear relationship between NO_x emission and the ratio N_d [17]. With increasing the ratio N_d, the NO_x emission is gradually reduced. Under the optimum condition, the NO_x emission attains 378 ppmv for coal No. 1 and 327 ppmv for coal No. 2. The PC combustion with PC rich/lean streams may have much influence on reducing NO_x emission. In the PC rich stream, the less oxygen content inhibits the formation of NO_x, and in the coal lean stream, NO_x formation is also limited because of the low temperature and less volatile nitrogen.

4. Utilization of new burners

According to the above experimental results, the new burners with coal rich/lean streams were designed and utilized in a 50 MWe thermal power station burning a low volatile coal (see Table 1, coal No. 3). In each corner of the tangentially fired furnace, the group of burners is assigned as secondary (1), primary (1), primary (2), secondary (2), secondary (3) and tertiary air from the bottom to the top in the burner zone. Because of the low volatile and high ash content in coal No. 3, the ignition was not stable in the furnace, especially under low load condition. In general, the boiler was only operated under more than 35 MWe load. Therefore, the burners of primary (1) air were retrofitted as the burner with coal rich/lean streams to improve coal ignition and burnout.

After retrofitting the burners, the average temperature near the burner of primary air (1) at each corner was detected by a radiation pyrometer. NO_x emission was measured through a flue gas analyzer. The results are compared with those before retrofitting the burners in Figs. 7 and 8.

In Fig. 7, the average temperature near the burner of primary air (1) increases as 30, 51 and 77 K, respectively, for 35, 40 and 45 MWe electricity load. The average temperatures after retrofitting

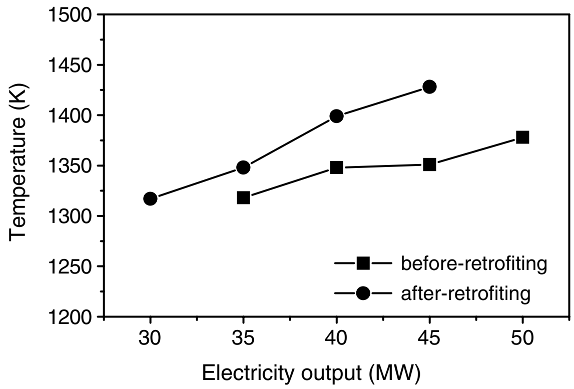

Fig. 7. The average temperature near coal burners in a 50 MWe utilized power station.

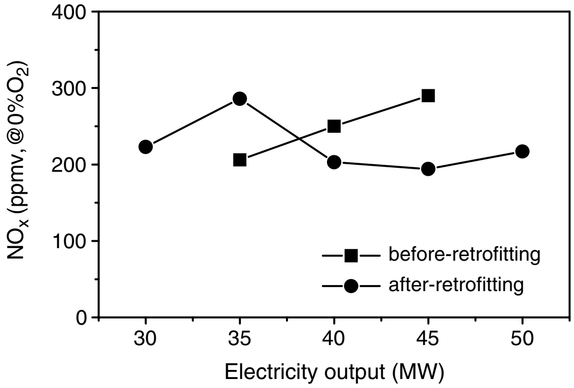

Fig. 8. NO_x emission from a 50 MWe utilized power station.

for 30 and 35 MWe load are almost the same as the temperatures before retrofitting for 35 and 40 MWe load, respectively. In addition, the average temperatures after retrofitting for 40 and 45 MWe load increase as about 50 K compared with the data before retrofitting for 45 and 50 MWe load. Obviously, due to the higher coal concentration in the coal rich/lean burners, the combustion temperature and efficiency will be enhanced to a higher level. The test results also show that the boiler efficiency increases about 3% after retrofitting the burners.

In Fig. 8, the NO_x emission before retrofitting increases with increasing electricity load from 70% to 90%, but the NO_x emission after retrofitting significantly reduces with increasing load. Because most of the NO_x is formed during combustion of volatile and char near the burner nozzle, the oxygen concentration and temperature in the frontal area of the coal flame have a significant influence on the NO_x formation. For conventional coal burners, increasing the electricity load enhances the temperature level in the furnace, and then, NO_x formation increases because oxygen concentration is not, but temperature is, the intrinsic factor. For the burners with coal rich/lean streams, increasing the electricity load significantly enhances the PC concentration, and the oxygen concentration is lower in the coal flames. Because the NO_x forms in the reducing atmosphere, increasing electricity load will depress NO_x formation because therein temperature is not, but oxygen concentration is, the intrinsic factor. Under low load conditions, the NO_x formation for the new burners is even higher than for conventional burners because the PC concentration decreases in the coal rich stream, and NO_x is formed in an oxidizing atmosphere, not in a reducing atmosphere as under high load conditions.

5. Discussion

Normally, in the design of coal burners, the selection of primary air ratio and velocity is related with the coal pulverizer and combustion system and may affect PC preparation, transport and flow pattern, even turbulence in furnaces. From the view of combustion, primary air is supplied to burn the volatiles produced during coal ignition. We can assume the oxygen in primary air and volatiles is a stoichiometric mixture. Because the direct ratio between heating value of coal and combustion air needed may be a constant (the ratio assumed as 3.75 MJ/Nm^3), the primary air ratio can be calculated by the ratio of the heating value of volatiles to that of coal as follows:

$$r_{pa} = \frac{V_{ar} Q_V}{\lambda Q_{net,ar}} \tag{1}$$

where V_{ar}—volatiles, as received basis; Q_V—heating value of volatiles, assuming

$$V_{ar} Q_V = Q_{net,ar} - FC_{ar} \cdot 32.8 \tag{2}$$

FC_{ar}—fixed carbon, as received basis; $Q_{net,ar}$—heating value of coal, as received basis; λ—air–fuel ratio, $\lambda = 1.2$.

Therefore, the coal concentration in primary air is given as follows:

$$\mu = \frac{1}{\rho V_o \lambda r_{pa}} \tag{3}$$

where ρ—air density; V_o—the total combustion air needed by coal per kilogram at stoichiometirc condition, assuming

$$V_o = Q_{net,ar}/3.75 \tag{4}$$

From Eqs. (1)–(4), we obtain:

$$\mu = \frac{3.75}{\rho V_{ar} Q_V} \tag{5}$$

The calculated results for coals No. 1–3 are showed in Table 3. In the utilized power station, because the velocity of the primary air should be enough to transport the PC into the furnace, a larger primary air ratio needs to be selected regardless of the less oxygen requirement for igniting low volatile coal. For example, the primary air ratio is designed as 25% for coal No. 3 in the 50 MWe thermal power station, but the calculated primary air ratio is 18.85% according to analysis of the volatile ignition. The actual coal concentration in the primary air is 0.58 kg(coal)/kg(air), but in Table 3, the calculated value is 0.79 kg(coal)/kg(air). Obviously, for coals with low volatile matter, the coal concentration in the primary air is lower than the optimum concentration to ignite the coal. This is why the fuel/air ratio is about 0.3–0.6 kg(coal)/kg(air) in normal coal burners, but the optimum concentration for low volatile coals may be 0.6–1.4 kg(coal)/kg(air) [13,14]. Therefore, PC concentrators are installed in the pipes to separate the primary air into two streams [15,18], and then they go to two separate burner nozzles. Both nozzles have a synergistic action for coal ignition because when the coal rich stream enters the furnace, it will firstly ignite and then the coal lean stream is ignited by it.

In addition, the above analysis has not considered the char ignition and the effect of temperature on the volatiles release rate, but it clearly shows why burners with coal rich/lean streams may improve low volatile coal ignition.

In conventional burners, increasing the furnace temperature will enhance NO_x formation. To improve the combustion efficiency of low volatile coal (that means higher flame temperature needed) is incompatible with reducing NO_x formation. However, utilization of burners with coal rich/lean streams may be a selected method, not only to achieve coal ignition and burnout but also to reduce NO_x formation.

NO_x formation may be influenced by the temperature and stoichiometric ratio in the coal flames near the burner zone. Increasing the temperature will increase the formation of thermal NO, especially for temperature environment more than 1773 K [20]. However, the temperature is shown to have a weak influence on fuel NO in turbulent, diffusion type, PC flames [20]. This could be attributed to the offsetting effects of volatiles production and stoichiometric ratio on NO formation at different temperatures. For burners with coal rich/lean streams, more volatiles are produced in a coal rich flame, and NO_x reduction is enhanced due to higher conversions of fuel N into precursory species. On the other hand, less volatiles are produced in coal lean flame, and thus, NO_x is not very likely to form due to less volatile N released.

Table 3
Calculated primary air ratio and coal concentration according to analysis of volatile ignition

	Coal		
	No. 1	No. 2	No. 3
r_{pa} (%)	15.62	13.38	18.85
μ (kg(coal)/kg(air))	0.60	0.90	0.79

6. Conclusions

Three low volatile coals were burned in tangentially fired furnaces with fuel rich/lean burners. Results show that the N_d value has significant influences on the distributions of temperature and char burnout. There exists an optimal N_d value, e.g. $N_{d,\mathrm{opt}} = 4.0$ for coal No. 1 and $N_{d,\mathrm{opt}} = 2.75$ for coal No. 2. Under the optimum condition, char burnout attains the best state and NO_x emission is relatively low. In conventional burners, increasing furnace temperature will enhance NO_x formation. However, utilizing burners with fuel rich/lean streams not only can improve the ignition and burnout of low volatile coal but also may reduce NO_x emission. In the coal rich stream of the burners, the optimum coal concentration is the reason for improved ignition of low volatile coal. In addition, more volatiles are produced, and NO_x reduction is enhanced due to higher conversions of fuel N into precursory species. In the coal lean stream, coal may be ignited by the near coal rich flame. Furthermore, less volatiles are produced in the coal lean flame, and thus, NO_x is not very likely to form due to less volatile N released.

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