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Industrial test on coal re-burning at a 600 MW utility boiler and NO_x reduction

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Abstract−This research conducts a series of industrial tests on coal reburning of a 600 MW pulverized coal boiler firing lignite, which is one part of a coal reburning demonstration project. When running steadily under 600 MW load, the boiler has an average NO_x emission of 274 mg/m^3 (O_2 content in flue gas is converted to 6%), the NO_x emission is reduced by 65.36%. In the meanwhile, loss of ignition (LOI) under coal reburning rarely increases. Three operation conditions - traditional air feeding, air staging and coal reburning - are realized, respectively, during the industrial tests, and the results indicate that coal reburning has the lowest NO_x emission, while the traditional air feeding has the highest NO_x emission. Under the test conditions, the higher the proportion of the reburning coal, the higher the NO_x control can reach.

Key words: Coal Reburning, Fuel Staging, NO_x, Industrial Test, Lignite

INTRODUCTION

1. Review on NO_x Control Technology

Nitrogen oxide emissions from coal combustion are the major contributors to a number of environmental hazards, including acid rain, high ground-level ozone concentrations, and elevated fine particulate levels. Therefore, there is an increasing need for the development and application of cost effective technologies for controlling these emissions.

The technology of NO_x control includes three types [1,2]: denitrogenation before the combustion, after the combustion and during the combustion. The first type controls the NO_x emission by getting rid of nitrogen from fuel or by using pure oxygen instead of air for reaction; thus the NO_x will not be formed due to the lack of nitrogen. However, this type of method is much too expensive for utility boilers and can hardly be taken into practice. The second method, denitrogenation after the combustion, also called as flue gas denitrogenation such as selected catalytic reduction (SCR), gets rid of NO_x by adding reductant or sorbent into the upper part of the furnace, where the substances will react with NO contained in the flue gas in chemical or physical mechanisms. This type of method can effectively reduce NO_x, but it requires high initial investment and running cost. The third type, denitrogenation during combustion, also called low NO_x combustion, controls NO_x emission by restraining or reducing NO during combustion. In practice this method has lower retrofit investment and running cost than the first two methods.

The history of low NO_x combustion technology can be divided into three stages. The first stage employed primitive low NO_x burner modification or operation parameter optimization, which might achieve 10-30% NO_x reduction. The second stage is air staging (AS). Modern AS consists of staging the combustion air in a number of streams, which are delivered to the furnace in convenient loca- tions. Air staging is intended to reduce the formation of NO_x by limiting the availability of NO promoters such as O2, O, and OH. Air staging achieves some 30-50% NO_x reduction. A typical air staging system usually sets over fire air (OFA) downstream of the primary combustion zone. The third stage is fuel staging, or reburning, which was first proposed by Wendt in 1973 [3]. In reburning, a "primary fuel" (fuel I) is burned to completion with an excess of "primary air" (air I), then "reburning fuel" (fuel II) is added for resetting reducing conditions, and finally combustion is completed with excess "burnout air" (air III). A basic reburning process typically provides 50-60% NO_x control. The reburning fuel can be gas, liquid, or solid [4].

The development of NO_x control technology has gone from the early practice of low NO_x combustion to the present flue gas denitrogenation, but that does not mean the end of low NO_x combustion. Since flue gas denitrogenation is highly effective but high cost, and low NO_x combustion is not so effective but low cost, the combination of the two methods will be the ideal choice in theory. In this model, NO_x should be first controlled low by low NO_x combustion, and then be further reduced by flue gas denitrogenation. With the lowest NO_x emission from the furnace, it is possible to reach the most economical flue gas denitrogenation [5,6].

2. Coal Reburning

Reburning has the highest NO_x control among the three low NO_x combustion methods mentioned above. In the case of lacking gas or liquid fuel, coal reburning may be the only choice [7]. In a typical coal reburning boiler, the furnace is divided into three zones: primary combustion zone, reburning zone and burnout zone. The primary zone is the region where 80-85% pulverized coal is injected and reacts with air, resulting in NO_x formed. The stoichiometric ratio (SR) of this zone is about 1.0. The reburning zone is directly above the primary zone, where the rest 15-25% pulverized coal is injected, used as reburning coal. NO contained in flue gas reacts with the reburning coal, forms radicals and then N_2. Generally, the SR in the reburning zone is 0.8-0.9. Finally, the unreacted fuel completes combustion in the burnout zone, where additional air is added. The

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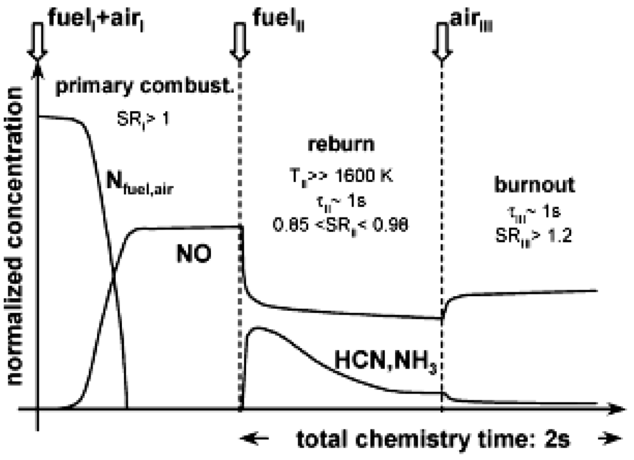

Fig. 1. Schematic presentation of nitrogen conversion in reburning (Edgardo, C. Z. et al.).

SR in the burnout zone is about 1.2.

DEMONSTRATION OF COAL REBURNING ON A 600 MW UTILITY BOILER

1. Introduction of the Demonstration Boiler

A demonstration project on the coal reburning was carried out on a 600 MW, tangentially fired utility boiler in Yuanbaoshan Power Plant in August, 2005. The designed fuel for the boiler was Yuanbaoshan lignite, and the pulverized coal was prepared by eight sets of direct mill systems with MPS mills. Four sets of burners were arranged in the four corners of the furnace. In each corner, eight primary air (PA) injectors were vertically furnished on different elevations, named from A, the bottom one, to H, the top one. The secondary air (SA) nozzles were vertically arranged on both sides of each PA nozzle. From bottom to top, the nozzle serial numbers were AA, AB, BC, CD, DD, EE, EF, FG, GH and HH. To enhance burnout, two close-coupled over fire air (CCOFA) nozzles, I and J, were arranged directly above the nozzle HH. While running with 600 MW load, seven PA injectors were taken into use in each corner, leaving one as a substitute.

2. Introduction on Coal Reburning Modification

The purpose of the coal reburning modification was to create three zones in the target furnace, which were primary zone, reburning zone and burnout zone. The target SR of the three zones was 0.95-1.0, 0.85-0.9 and 1.167, respectively. By modification, all the PA injectors were kept in their original status without any change. PA injectors G and H were set as reburning coal entrances. In order to create burnout zone, a separated over fire air (SOFA) compartment was installed certain distances above the nozzle HH. The SOFA compartment was vertically divided into three sections, K, L and M, from bottom to top. With the installation of SOFA, some original SA nozzles should be changed to keep the SA flow areas equal to the areas before modification. The space from the elevation of injector A to the elevation of injector G was the primary combustion zone, the space from the elevation of injector G to the elevation of injector K was the reburning zone, and finally the space above the elevation of injector K was the burnout zone. The pre and post modification burners are shown in Fig. 2 and Fig. 3 below.

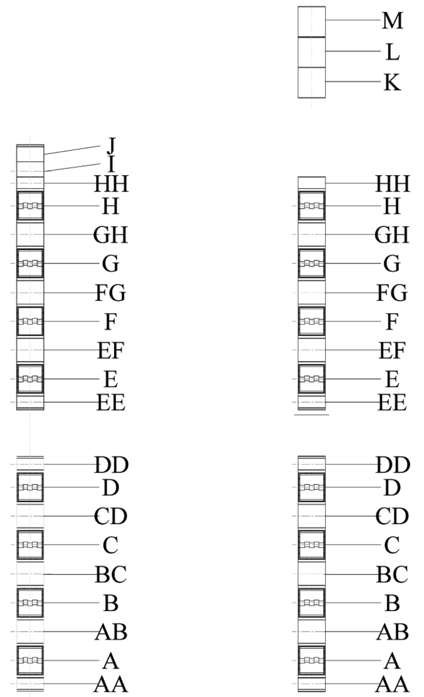

Fig. 2. Burner nozzles arrangement before and after modification.

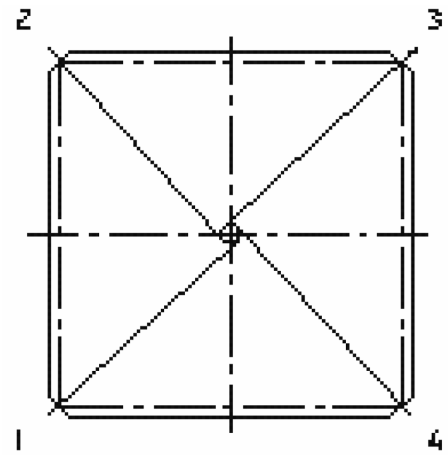

Fig. 3. Plan view of the burners.

By calculation, the residence time and the SR of different combustion zones are shown in Table 1.

INDUSTRIAL TESTS

Industrial tests were performed in order to study the NO_x emission changes before and after modification, and the compacts of burners on boiler running after coal reburning. The pre-modification test, considered as the baseline test, was carried out just before the retrofit. Various input fractions of reburning coal and air feeding conditions were set to determine NO_x emission level as well as LOI.

All the tests mentioned below were performed with the unit kept running at 600 MW±5% load. Each test lasted for four hours, with all the major operating parameters kept stable during the test. Before each test, sootblowing was taken into operation so as to keep

Table 1. Ultimate and proximate analysis of the test coals

Combustion conditions	M_{ar} (%)	A_{ar} (%)	V_{ar} (%)	FC_{ar} (%)	C_{ar} (%)	H_{ar} (%)	S_{ar} (%)	O_{ar} (%)	N_{ar} (%)	$Q_{ar,net}$ (MJ/kg)
Traditional	24.66	25.69	22.27	27.38	36.08	2.4	0.9	9.71	0.56	13.14
Air staging	20.87	36.20	18.82	24.11	31.79	2.21	1.00	7.5	0.43	11.52
Coal reburning	23.21	29.92	20.55	26.32	34.24	2.12	0.89	8.95	0.67	12.48

Table 2. The SR and the proportion of SOFA to SA in various combustion zones

Reburn burners	f_{rc} (%)	γ_{OFA} (%)	SR_{PZ}	SR_{RZ}	SR_{BZ}
G, H	28.57	22.51	0.994	0.925	1.19
H	14.28	22.90	1.02	0.9	1.21

the same initial furnace condition for all the tests. The coal samples collection was first taken one hour before the test, then the collection was repeated until the test was finished. The temperature of flue gas was measured by thermocouples. The content of O_2 and NO in exhausted flue gas was measured by flue gas analyzer, TESTO 350XL. All the above sampling points were arranged in a grid, on the outlet of air preheaters. The flyash sampling points were in the location of the electrostatic precipitator (ESP). The slag samples were collected in the slag collectors below the furnace. The operating parameters concerned with the tests were recorded from the operating panel. The furnace temperatures on different elevation were determined in the location of the observation holes around the furnace, by using a pyrophotometer.

The ultimate and proximate analysis of the test coals is shown in Table 1. The values reveal that the three major test coals have similar contents in ultimate and proximate and have no more than 10% error in heating value.

TEST RESULTS AND ANALYSIS

For the purpose of comparing NO_x emission in different test cases, all the values indicated in the flue gas analyzer were converted from the volume fraction in ppm to mass fraction in mg/m^3, and the NO_x concentrations in the flue gas with other oxygen content were then calculated in standard oxygen content, 6%. According to the China Government Standard of NO_x emission from Thermal Power Plants (GB13223-2003), the conversion equation is as follows:

$$[NO]=2.05\times[NO]_0\frac{21-x}{21-O_2}$$

Where 2.05 means that 1 L/L of NO is equal to 2.05 mg/m^3.

A baseline test was first carried out before boiler retrofit. The results have shown that the boiler has high NO_x emission of 791 mg/m^3, and a quite low LOI, 0.35%.

1. Reburning Coal Input Fraction

The effects of the reburning coal proportion over the total coal input on NO_x emission were first determined. Seven PA injectors were taken into use and one as a substitute. When all the coal injectors were kept the same heat input, each elevation of injectors shared 1/7 total heat input. If the injector G was idle, only injector H ran as reburning coal feeder; here the input fraction of reburning coal took 14.28% of the total coal input. If the idle one was injector F, then injectors G and H were both used as reburning coal feeders; here the input fraction of reburning coal was 28.57% the total boiler heat input. The SA kept a fixed arrangement along the various nozzles when the tests on changing the reburning coal fraction were shifted.

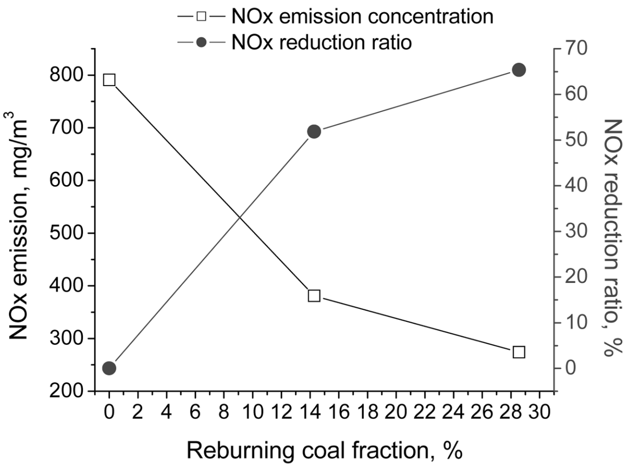

Fig. 4. Effects of reburn coal fraction on NO_x emission.

As shown in Fig. 4, the boiler has a significant decrease in NO_x emission when the coal reburning is employed. Meanwhile, NO_x emission reduces with the increase of the reburning coal fraction to the total coal input. While the single G injectors are used, the boiler has a NO_x emission of 381 mg/m^3, and 51.83% reduction ratio to the baseline test. While the G and H injectors are both used, the boiler has an NO_x emission of 274 mg/m^3, and 65.36% reduction ratio to the baseline test.

According to the operating data, the air flow and the coal injection from various nozzles, the SR in various combustion zones, as well as the proportion of SOFA to the total air flow is calculated. The result reveals that the average SR in the outlet of the primary zone, reburning zone, and the burnout zone is about 1.0, 0.91 and 1.2, respectively. The values are well consistent with the requirements of a reburning process.

2. Combustion Conditions

In a typical coal reburning process, fuel staging and air staging are both contributors to NO_x reduction. In order to research the individual contributions of fuel staging and air staging on the NO_x reduction, three combustion conditions - traditional air feeding, air staging and fuel staging - were set to compare each NO_x emission. In the traditional condition, no air or fuel staging was set, which was exactly the condition in the baseline test. When the injector H was set in idle and the lower seven PA injectors were set to work, the boiler ran under air staging condition. While the injectors G were in idle whereas the other seven injectors in work, a fuel staging condition, namely coal reburning case, was set. All SA arrangements

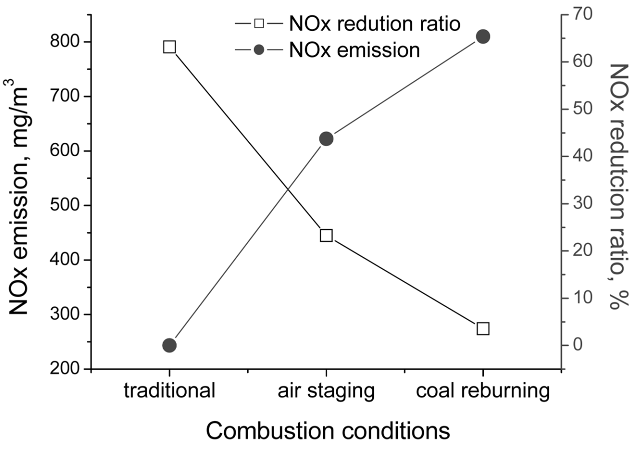

Fig. 5. Effects of the secondary air feeding on NO_x emission.

kept no changes among the three tests. The NO_x emissions over the three tests are illustrated in Fig. 5. In the case of air staging, the boiler has an NO_x emission of 445 mg/m^3, and the reduction ratio to the baseline case is 43.74%. The value is higher than that under coal reburning condition. It proves that it is the reburning coal that is injected into injectors G and H, then reduced NO_x formed in the primary combustion zone.

3. Loss of Ignition

On the LOI of the three tests, there is no obvious distinction (See Fig. 6). The results seem to break the common rule that LOI will rise with deeper staging combustion. A possible explanation is that the boiler's furnace is high enough that the retrofit has hardly any effect on pulverized coal burnout.

4. Furnace Temperature Profile and Slagging

The furnace temperature profiles before and after modification are illustrated in Fig. 7. The data of the post-modification come from the test with the 28.57% reburning coal fraction. The average temperature after the modification is lower than that before the modification. Over the lower half part of the furnace, the average temperature lowers nearly 150 to 180 degrees centigrade. This field is the exact location where the burners are placed. The highest temperature point moves up by about 5 meters. The elevation of the point

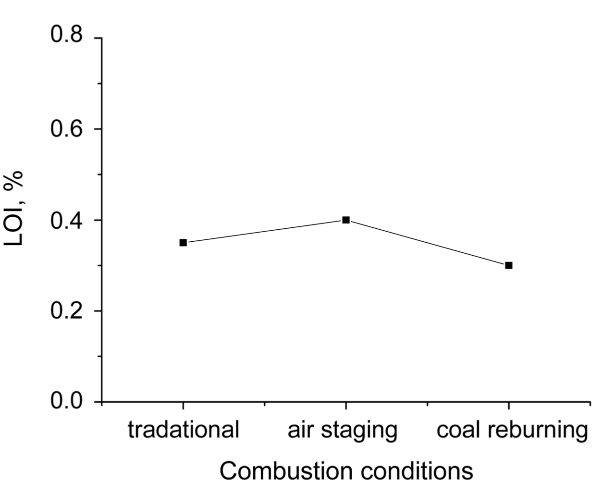

Fig. 6. Effect of the combustion conditions on LOI.

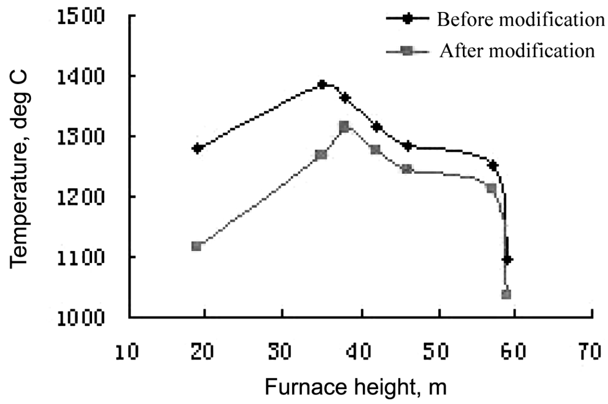

Fig. 7. Furnace temperature profile before and after modification.

is just where the SOFA is installed. All the trends indicate that after modification, the firing of pulverized coal is delayed, and the fire is lengthened. The temperature field after modification tends to be more reasonable to reduce NO_x emission, and has no more compacts on coal burnout in the meanwhile.

A question raised here is that integral temperature level under coal reburning condition is lower than the level under traditional air feeding condition. This phenomenon can be explained by the furnace slagging changes. The fuel, Yuanbaoshan lignite, has a strong slagging trend due to its relevant low softening temperature, which is less than 1200 degrees centigrade. Under traditional air feeding condition, the slagging process becomes severe owing to the concentrated supply of air and fuel into the primary combustion zone. After modification, the air feeding is staged, and the highest temperature point moves up. As a result, slagging in the furnace becomes lightened. The improvement of slagging increases heat absorption of water-cooled walls which brings the decrease of the integral furnace temperature level. The slag flow on the slag collectors can confirm the explanation. Firing the coal with similar ash content, the slag flow under coal reburning obviously increases compared to the traditional air feeding case.

CONCLUSIONS

1. The coal reburning on the 600 MW utility boiler has proved to be successful with a high NO_x reduction from 791 mg/m^3 before modification to 274 mg/m^3 after modification. The reduction ratio is 65.36%.

2. The greater the fraction of the reburning coal, the higher the NO_x control can reach.

3. The coal reburning process brings higher NO_x reduction than the air staging process for the demo boiler.

4. LOI has not obvious distinction before and after modification. This may be because the demo boiler's furnace is large enough that no visible effects on LOI are detected.

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NOMENCLATURE

A_{ar} : mass fraction of ash in coal as received [%]
f_{rc} : mass fraction of reburn coal [%]
FC_{ar} : mass fraction of fixed carbon in coal as received [%]
H_{ar} : mass fraction of Hydrogen in coal as received [%]
M_{ar} : mass fraction of water in coal as received [%]
N_{ar} : mass fraction of Nitrogen in coal as received [%]
[NO] : NO content converted to 6% of oxygen content [mL/L]
$[NO]_0$: the original NO content measured by analyzer [mL/L]
O_{ar} : mass fraction of Oxygen in coal as received [%]
$Q_{ar,net}$: net quality released by fully combustion of 1 kg coal as received [MJ/kg]
S_{ar} : mass fraction of Sulfur in coal as received, [%]
SR_{BZ} : stoichiometric ratio in the outlet of the burnout zone
SR_{PZ} : stoichiometric ratio in the outlet of the primary zone
SR_{RZ} : stoichiometric ratio in the outlet of the reburning zone
V_{ar} : mass fraction of volatile in coal as received [%]
x : standard oxygen content in flue gas, 6%
γ_{OFA} : proportion of the SOFA flow to the total air flow [%]

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