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Research on the Modification of Coal Adaptability and Carbon Emissions Reduction Technology for Coal-Fired Boilers

Dan Peng [1], Ben Wang [2,*,†], Xingfei Cai [3,*,†] and Lei Bei [2]

1 Henan Engineering Technology Research Center for Energy Conversation and Environmental Protection in Power Plant, Zhengzhou Electric Power College, Zhengzhou 450000, China
2 State Key Laboratory of Coal Combustion, Huazhong University of Science and Technology, Wuhan 430074, China
3 Shenzhen Zhongyuan Environmental Technology Co., Ltd., Shenzhen 518054, China
* Correspondence: benwang@hust.edu.cn (B.W.); hkbluemoon@126.com (X.C.)
† These authors contributed equally to this work.

Abstract: In order to solve the problems of the high temperature of flue gas, low boiler efficiency, and the high concentration of nitrogen oxide (NOx) emissions for a 330 MW boiler fired with lean coal in a power plant, an adaptation modification by using different type of coals in the power generation unit (including pulverizing system, burners, heating surface, and so on) was carried out. The performances of boilers were tested under different combustion conditions before and after the modification. The results of the test show that the volatile content is higher and easy to burn out, and the combustible content of fly ash and slag are greatly reduced after the change in coal type (while lean coal is changed into bituminous coal). At the same time, the low-temperature economizer can greatly reduce the flue gas temperature, thus increasing the efficiency from 90.36% (lean coal, corrected) to 92.71% (bituminous coal). After the change in coal type (lean coal to bituminous coal) and the shift to low-nitrogen combustion (using low-nitrogen burner and OFA technology), the flame temperature in the main combustion area of the boiler decreases, the thermal-type NOx is reduced, and the volatile content of bituminous coal is higher in the anoxic atmosphere of the main combustion zone where the excess air coefficient is small. The intermediate reductive products tend to produce more, which can restrain and reduce NOx. Therefore, the concentration of NOx emissions can be greatly reduced. NOx average emissions at the economizer outlet decreased by 68%, from 864 mg/Nm^3 to 279.4 mg/Nm^3. A low-temperature economizer uses waste heat to heat feed water, which reduces coal consumption by about 1.32 g/(kW·h). The coal consumption for power supply after modification is reduced by 9.83 g/(kW·h) and the annual energy saving is 16,776 tons of standard coal, while the total carbon dioxide emissions reduction is 41,213.60 tons after the unit modification.

Keywords: coal adaptability; comprehensive modification; carbon emission reduction technology; pulverizing system; boiler performance; NOx

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1. Introduction

Driven by the realization of the national goal of "carbon peak and carbon neutrality", the efficient and clean combustion of coal-fired units is a major demand in China. Recently the government issued an "Implementation Plan for Carbon Peak and Carbon Neutralization Supported by Science and Technology 2022–2030", to promote the low-carbon development of coal-fired power plants [1,2]. Methods such as reducing unit coal consumption and improving boiler combustion efficiency are key technologies. According to the present characteristics of the existing coal-fired units and the fluctuation in the coal market, carrying out coal type adaptability modification is one of the main technologies to reduce carbon emissions and improve boiler fuel adaptability and combustion efficiency.

The current research shows that some power plants have adopted the method of changing the fuel from lean coal to bituminous coal, or mixing and blending different coal types to adapt to boilers [3–5] and expand the range of coal types used in boilers [6–8]. However, this technology only optimizes the coal quality, has little adaptability, less changes in boiler efficiency, and is likely to cause adverse effects such as boiler slagging. In order to reduce NOx, researchers adopted air staging + low-nitrogen burner technology [9,10]. This technology has obvious effects on reducing NOx, but it also brings certain problems, such as: superheater temperature is too high, The quantity of desuperheating water increases, the carbon content of fly ash increases and so on.

Generally, compared with lean coal boilers, bituminous coal boilers have higher fuel burnout rate and higher boiler efficiency under the same boiler capacity and combustion mode. Given that the burnout rate of lean coal is low, a low degree of air classification degree is adopted while using the low-nitrogen method in order to ensure combustion efficiency. The oxygen content in the main combustion area is sufficient and the temperature in the combustion area is high, resulting in high NOx emissions. The NOx concentration is 30% to 80% higher than that of bituminous coal boilers of the same capacity.

To realize the coal type change from lean coal to bituminous coal, it is necessary to reform the boiler pulverizing system, boiler system and relative auxiliary equipment [11,12]. Not only is the boiler combustion system required to adapt to coal type changes, but also there is an influence of fuel change on the safety of each system, especially on the pulverizing system and the heating surface area. Due to the high volatile content and good ignition performance of the bituminous coal, it is necessary to lower the outlet temperature of the pulverizer and the temperature of the supply air. In order to reduce NOx emissions and avoid the slagging problem in the furnace caused by fuel changes to bituminous coal and deep air classification, overall modification of the burners is needed [13]. The temperature at the outlet of the economizer may rise and bare tube economizers shall be replaced by H-type fin tube economizers to reduce the economizer outlet temperature. For recovering flue gas waste heat and improving the overall unit efficiency, an exhaust gas heat recovery method such as a low-temperature economizer can be considered [14] for further energy savings.

For a 330 MW lean coal boiler, this paper researches and proposes the coal type adaptability modification technology, which includes pulverizing system modification, a low-nitrogen combustion equipment retrofit, economizer modification, and adding a low-temperature economizer. After comparing and analyzing parameters such as boiler efficiency, NOx emissions concentration, and coal consumption under different combustion conditions, and evaluating the effect of the coal types' adaptability, technical approaches and the basis for the realization of carbon emission reduction targets for coal-fired units are provided.

2. Overview of the Equipment Configuration before Modification

A 330 MW boiler was originally designed to use Pingdingshan lean coal, of HB-1025/18.2-PM7. The steam output is 1025 t/h, the main steam pressure is 18.2 MPa, the main steam and reheat steam temperature is 540 °C, and the electric output capacity is 330 MW, with π-type layout, natural circulation, primary intermediate reheating, balanced ventilation, subcritical pressure, four-corner tangential combustion, and dry bottom. The cross section of the furnace is 14.048 $\times$ 11.858 m, the pulverizing system is equipped with four cylindrical steel ball mills of model MTZ35.70-III, and the pulverized coal is transported by hot primary air in the middle storage system. The steam turbine is a 300 MW condensing unit with subcritical, primary reheat, double cylinder, and double exhaust steam, produced by Harbin Boiler Company Limited, Model N300-16.7/537/537.

At present, the main boiler problems when using lean coal are as follows: high exhaust gas temperature, low reheat steam temperature, the slagging tendency of the water wall in the burner area, and high NOx emissions concentration.

3. Modification Plan

3.1. Coal Analysis

The designed coal has a moisture content of 14.20%, volatile content as-received Var of 25.74%, ash content less than 12.89%, and a calorific value of 22.63 MJ/kg. The analysis is shown in Table 1.

Table 1. Analysis of design coal.

Item	Elemental Analysis (%)					Proximate Analysis (%)				Net Calorific Value ($MJ \cdot kg^{-1}$)
	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	V_{ar}	M_{ar}	A_{ar}	FC_{ar}	$Q_{net,ar}$
Original design coal	57.20	2.25	3.11	1.17	0.34	14.27	8.08	27.85	49.80	20.91
Original check coal	63.36	2.55	3.68	0.94	0.44	11.87	6.33	22.70	59.10	23.41
New Design Coal	58.40	3.38	8.20	0.83	2.10	25.74	14.20	12.89	47.17	22.63
New check coal	54.02	3.08	5.76	0.94	1.30	17.77	11.10	23.81	47.32	20.72

3.2. Specific Modification Plan

With bituminous coal, the high temperature of hot primary air could lead to explosion accidents, so the reorganization of reasonable airflow distribution and modification of burners are needed to realize further air classification and reduce slagging, as well as decreasing NOx emissions and improving boiler efficiency.

The detailed modification plan is as follows:

(1) Pulverizing system

When burning lean coal, hot air feeding is adopted. Since the fuel is changed to bituminous coal, exhausted air to convey pulverized coal is used to transfer coal power to lower the temperature and ensure safe combustion while the original mills, PC bunker, coarse powder separators, and cyclone separators are retained. At the same time, the air volume of the pulverized coal discharge fan should be increased, and the pipeline between the outlet of the discharge fan and the burners should be redesigned. The connection between each burner nozzle and the exhauster is shown in Table 2.

Table 2. Correspondence between burner nozzle and exhauster.

Item	A	B	C	D
Burner number after retrofit	A-1, A-2, A-3, A-4	B-1, B-2, B-3, B-4, D-1, D-3	C-1, C-2, C-3, C-4, D-2, D-4	E-1, E-2, E-3, E-4

Note: The burners are labeled A, B, C, D, and E, from bottom to top, with a total of five layers (four in operation and one on standby), and the burners of each layer are labeled 1, 2, 3, and 4 in the four corners of the furnace.

Part of the secondary cold air from the forced draft fan and the hot secondary air from the air preheater are evenly mixed with the circulating exhausted air, and then sent to the coal mill.

The branch pipeline with mixed air from hot secondary air and the pressurized cold secondary air is designed as the bypass inlet air of the powder discharge fan, while the primary air after fuel modification comes from the cyclone vent and the bypass air. The flow diagram of the modification design is shown in Figure 1.

(2) Low-NOx burner modification

SOFA nozzles are added above the main burner of the boiler furnace and can easily swing in four directions (up, down, left, and right). Moreover, one can adjust the primary and secondary air elevation and burner nozzle cross-section areas. At the same time, the burner adopts vertical concentration and dilution separation technology.

(3) Economizer modification

Replace the two-return tube economizer with an H-type finned tube economizer.

(4) Low-temperature economizer

A low-temperature economizer is installed in the flue duct after the air preheater. The circulating water is introduced from the condensed water of the low-temperature heater system and is in parallel with the low-temperature heater system.

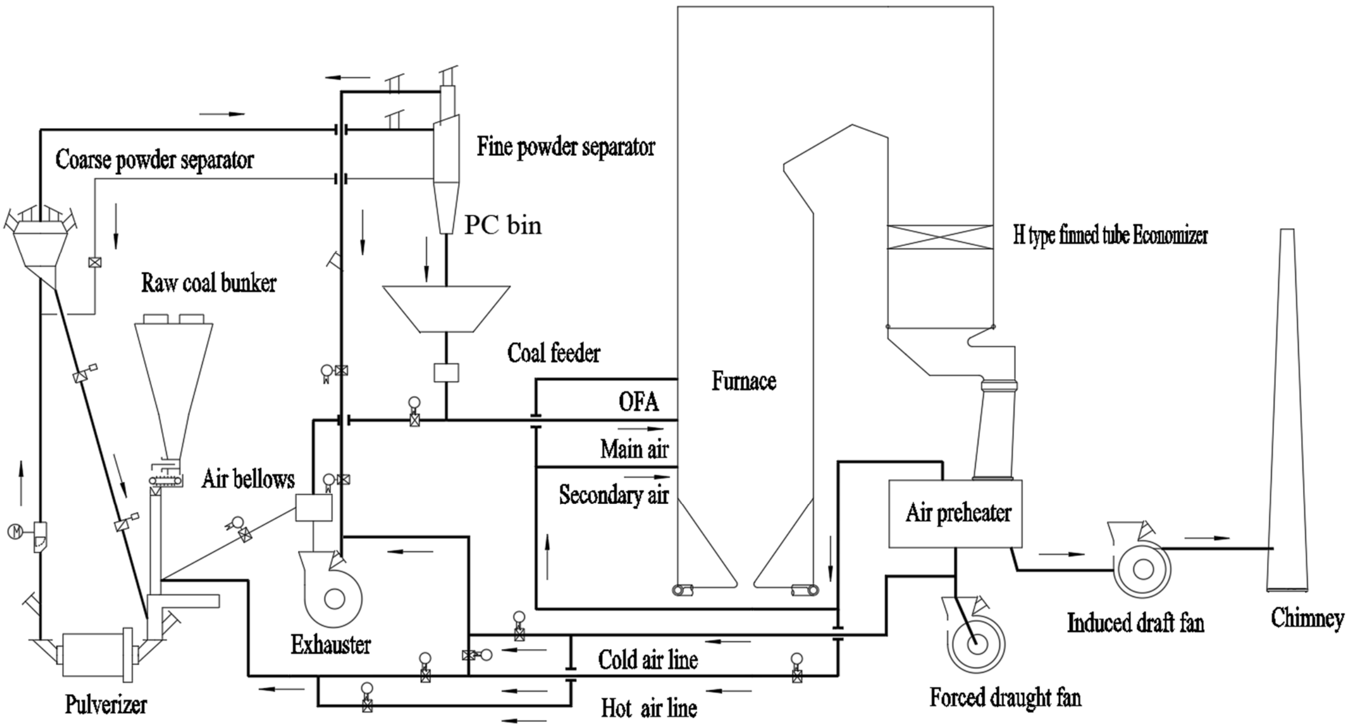

Figure 1. Flow diagram of the modification scheme of the milling system.

4. Experimental Research Methods

Tests were carried out on the boiler before and after the modification, and the results were compared in terms of exhaust gas temperature, boiler efficiency, combustion degree, flue gas components, and so on.

4.1. Test Conditions

Before modification, the test condition was from A-01 to A-03; after modification, they were B-04 to B-07, and the specific working conditions were as described in Table 3.

Table 3. Test conditions.

Item	Working Condition A-01	Working Condition A-02	Working Condition A-03	Working Condition B-04	Working Condition B-05	Working Condition B-06	Working Condition B-07
Load/MW	319.40	318.80	265.30	307.70	308.40	305.70	249.60
Mill in operation/set	3		2	4	4	3	3
exhauster in operation/set	ABD	ABCD	ABD	ABC	ABC	ABC	ABC
Low temperature economizer in operation or not	NO	NO	NO	In operation	In operation	NO	NO

4.2. Corresponding Coal Analysis

The lean coal for test conditions A-01 to A-03 was of low as-received volatile content, about 11%, and with a low heat value (as received) of about 22.00 MJ/kg. For conditions B-04 to B-07, bituminous coal of higher volatile content, about 26%, was adopted. The bituminous coal used in the test had a similar volatile content to the design coal and a calorific value close to that of the check coal. The overall quality of the test coal was worse than that of the design coal, and the coal quality in the thermal test after the modification was stable. The details are shown in Table 4.

Table 4. Coal parameters used in different working conditions.

Working Condition	Elemental Analysis (%)					Proximate Analysis (%)				Net Calorific Value (MJ·Kg $^{-1}$)
	Car	Har	Oar	Nar	Sar	Var	Mar	Aar	FCar	Qnet, Our
A-01	53.17	2.34	3.44	0.89	1.08	11.01	7.94	31.14	49.91	22.11
A-02	52.89	2.44	3.09	0.91	1.06	11.21	7.53	32.09	49.17	22.12
A-03	51.69	2.37	4.66	0.92	0.90	12.05	6.48	32.98	48.49	17.31
B-04	53.97	3.52	3.52	0.93	0.81	26.76	9.70	22.02	41.53	20.74
B-05	53.90	3.46	3.46	0.92	0.81	26.40	10.50	21.59	41.51	20.56
B-06	53.96	3.55	3.55	0.93	0.85	26.59	9.30	22.25	41.86	20.72
B-07	54.97	3.48	8.44	0.95	0.85	26.04	9.00	22.28	42.69	20.83

4.3. Test Method

The test was carried out according to the Performance test code for utility boiler. The flue gas components were measured by a MSIEURO flue gas analyzer produced by Drager. A calibration-qualified K-type compensation wire rated first class was connected to the TESTO925 temperature digital display instrument to measure the exhaust gas temperature point by point. The flue gas composition and temperature were calibrated by the equal-section grid method according to the number of points specified in the national standard GB10184-88. Fly ash and large slag were sampled for laboratory analysis [15].

5. Analysis and Discussion

5.1. Comparative Analysis of Burnout Rate and Exhaust Temperature before and after Modification

Combustibles in fly ash and slag decreased significantly after the fuel changed to bituminous coal. See Figure 2 for details. The average fly ash combustibles content in the B-04 and B-05 conditions after fuel change modification and with a low-temperature economizer in operation was reduced by 2.69% compared to A-01 and A-02 which is 2.04%. Under the test coal and 250 MW load conditions, the combustible content of fly ash in condition B-07 was 1.61%, which is 1.32 % lower than that in condition A-03 which is 2.93%.

The average slag combustibles content in B-04 and B-05 conditions after the fuel change modification and with a low-temperature economizer in operation was 3.39% lower than that of A-01 and A-02. In the B-07 condition with test coal and at a 250 MW load, the slag combustible content was 1.73%, which is 0.91% lower than that in condition of A-03 which is 2.64%.

The main reasons for the decrease in combustibles in fly ash and slag are as follows: (1) after changing poor coal into bituminous coal, the volatile content increased from 11.00% to 26.00%, and the fly ash decreased from 27.85% to 12.89%, making it very easy to burn and burn out. (2) Because of the low-nitrogen burner adopts vertical concentration and dilution separation technology, the concentration of pulverized coal at the outlet of the burner can be increased and the secondary air of the burner can be supplied over time, which can enhance the effect of combustion and burnout.

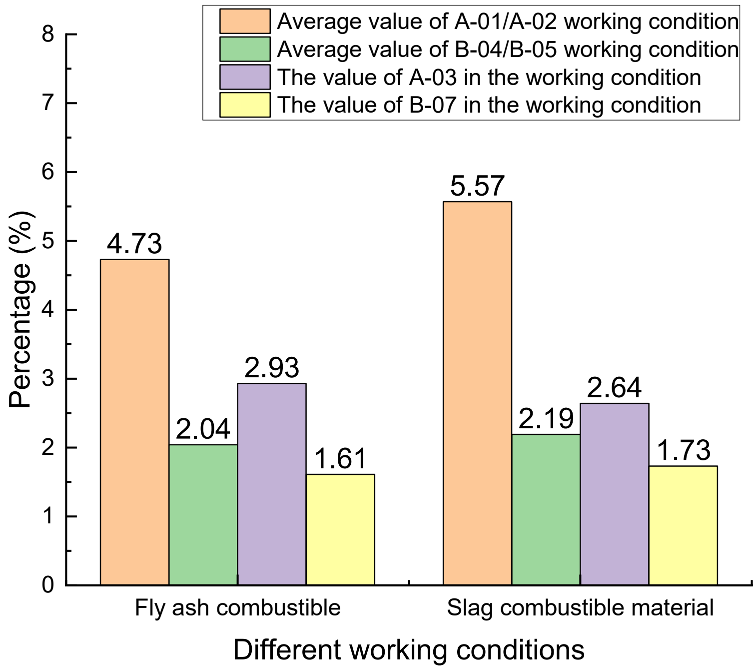

Figure 2. Fly ash and slag combustibles under different working conditions.

The average corrected exhaust gas temperature for B-04 and B-05 was 139.4 °C, a decrease of 5.30 °C from the 144.73 °C average from A-01 and A-02. Under a load of 250 MW, the average corrected boiler exhaust gas temperature in condition B-07 was 138.53 °C, 6.74 °C lower than that of A-03 before modification, which was 145.27 °C, as shown in Figure 3. The main reason for the temperature drop is that a partial H-type finned tube economizer was used instead of a plain-tube economizer, which increased the heating area of the economizer and reduced the outlet temperature of the economizer.

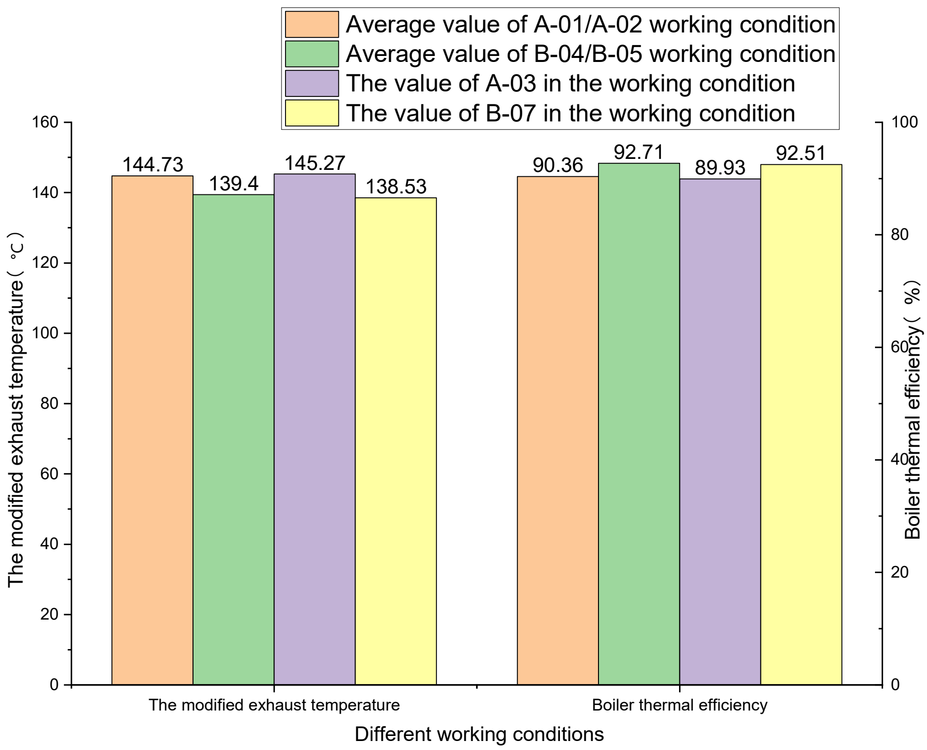

Figure 3. Exhaust temperature and boiler thermal efficiency under different working conditions.

5.2. Comparative Analysis of Boiler Efficiency before and after Renovation

Loaded with 320 MW, two boiler thermal efficiency tests were carried out with the tested coal under working conditions A-01 and A-02. as shown in Figure 3. By using the test coal, the measured thermal efficiency of the boiler in working conditions A-01 and A-02 was 90.64% and 90.44%, respectively, a difference of 0.2%; after the correction, the thermal efficiency of the boiler in working conditions A-01 and A-02 was 90.25% and 90.46%, respectively, a difference of 0.21%. The average value of the two test results is 90.36%; using the test coal and given a 265 MW load, the measured thermal efficiency of the A-03 boiler in working condition was 90.17%, and the boiler thermal efficiency after correction was 89.93%.

After the modification of adaptability of boiler coal, a boiler efficiency test was carried out under four working conditions, B-04, B-05, B-06, and B-07. When the test coal was used, the measured efficiency of the boiler was 92.86%, 92.70%, 92.60%, and 92.55%, respectively; and changed to 92.79%, 92.62%, 92.55%, and 92.51%, respectively, after being corrected, as shown in Table 5. When the bituminous coal was modified and the low-temperature economizer was installed, the average boiler efficiency of B-04 and B-05 after modification was 92.71%, which is (after correction) 2.35% higher than that of A-01 and A-02, namely 90.36% when lean coal is burned and the modification has not yet been adopted. When using the test coal and loaded with 250 MW, the measured boiler thermal efficiency in working condition B-07 was 92.55%, and 92.51% after correction, which is 2.58% higher than that under the working condition A-03 (namely 89.93%, after being corrected when burning lean coal) before modification.

Table 5. Test results of boiler thermal efficiency.

Serial Number	Name	Working Condition A-01	Working Condition A-02	Working Condition A-03	Working Condition B-04	Working Condition B-05	Working Condition B-06	Working Condition B-07
1	Unit load (MW)	319.40	318.80	265.30	307.70	308.40	305.70	249.60
2	Main steam flow ($t \cdot h^{-1}$)	1055.00	1049.00	842.00	1000.60	999.70	1000.30	786.20
3	Ambient temperature (°C)	35.97	37.00	37.20	28.90	29.30	26.90	26.40
4	Ambient relative humidity (%)	43.30	44.00	41.40	63.40	61.40	68.10	68.20
5	Atmospheric pressure (kPa)	99.72	99.72	99.99	100.76	100.80	100.80	100.80
6	Flue gas oxygen (%)	5.67	5.52	6.66	4.68	4.76	5.33	5.45
7	Flue gas temperature (°C)	154.69	156.35	156.35	144.40	146.20	143.90	142.70
8	Ash combustibles (%)	4.70	4.76	2.93	1.96	2.12	1.96	1.61
9	Slag combustibles (%)	4.68	6.46	2.64	2.34	2.03	2.12	1.73
10	Heat loss due to exhaust gases q_2 (%)	6.10	6.08	6.67	5.80	5.94	6.07	6.14
11	Chemical incomplete combustion loss q_3 (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	Mechanical incomplete combustion loss q_4 (%)	2.59	2.80	2.28	0.76	0.73	0.60	0.73
13	Leakage heat loss q_5 (%)	0.41	0.41	0.51	0.43	0.43	0.55	0.43
14	Ash residue heat loss q_6 (%)	0.26	0.27	0.38	0.17	0.18	0.17	0.17
15	Total heat loss (%)	9.36	9.56	9.83	7.30	7.40	7.45	7.14
16	Boiler thermal efficiency (%)	90.64	90.44	90.17	92.86	92.70	92.60	92.55
17	Corrected flue gas temperature (°C)	144.20	145.26	145.27	138.62	140.17	139.41	138.53
18	Corrected boiler efficiency (%)	90.46	90.25	89.93	92.79	92.62	92.55	92.51

The heat efficiency of the boiler adopts the heat-loss method, as in Equation (1):

$$\eta = 100 - (q_2 + q_3 + q_4 + q_5 + q_6) \quad (1)$$

where q_2—heat loss due to exhaust gases; q_3—chemical incomplete combustion loss; q_4—mechanical incomplete combustion loss; q_5—leakage heat loss; q_6—ash residue heat loss.

On the premise of the normal combustion of a boiler, the loss of a boiler is mainly q_2 and q_4, while q_3 and q_5 are smaller, as detailed in Table 5. q_3 and q_5 changed little before and after the adaptation. The main reasons for the improvement in boiler efficiency are as follows: (1) after the change of poor coal to bituminous coal, the volatiles are greatly increased, the coal quality and combustibility are easy to burn and burn out, the fly ash and slag combustibles are obviously decreased, and q^4 and q^6 are greatly reduced. (2) Using part of the H-type finned tube economizer instead of the plain tube economizer, the heating area of the economizer is increased, and the outlet temperature of the economizer is decreased, so that the smoke emission loss q_2 is greatly reduced.

q_2, q_4, and q_6 decreased, but q_3 and q_5 were basically unchanged, so the boiler thermal efficiency η increased.

5.3. Comparative Analysis of NOx Emissions before and after Modification

After the modification, the average NOx content at the outlet of the economizer was 279.4 mg/Nm^3 under the test conditions of B-04 and B-05 when the two low-temperature economizers were installed. The result was reduced by about 68% compared with the average NOx content of A-01 and A-02 before modification, namely 864.0 mg/Nm^3. After the modification, the average oxygen content of the economizer outlet in working conditions B-04 and B-05 was about 2.85%, the mechanical incomplete loss of the boiler was 0.57%, and the content of slag combustible material was 2.19%. Therefore, the NOx content in the flue gas at the economizer outlet can be further adjusted to achieve the goal of NOx reduction. When using the test coal and loaded with 250 MW, the average NOx content in the flue gas at the economizer outlet of the boiler in working condition B-07 is 257.8 mg/Nm^3, a reduction of 70% compared to the average NOx content in working condition A-03, which was 865 mg/Nm^3 before modification. The details of NOx emissions are shown in Table 6. The main reasons for the sharp drop in NOx concentration are:

(1) After the modification, the higher the volatile content of bituminous coal (V_{daf} > 25%), the more intermediate products NH_3 and HCN are generated in the initial combustion reaction in the oxygen-deficient atmosphere of the main combustion zone with a small excess air coefficient. The NOx produced can be inhibited and reduced by these intermediate reducing products [16–18].

(2) Thermal NOx originates from the oxidation of N_2 in the air to NO during the combustion process, which occurs mainly in the high-temperature region above 1500 °C. The flame temperature and NOx generation increased exponentially, and the thermal NOx produced increased with the increase in temperature. After the lean coal is replaced by bituminous coal, the temperature of the flame center in the main combustion zone of the boiler is generally lower than 1500 °C, and the thermal NOx generation is almost negligible [19,20].

(3) Air distribution can effectively control the formation of NOx. The formation of NOx in boiler exhaust flue gas is related to the residence time of coal particles in the reducing atmosphere of the boiler and the depth of air distribution. However, with the deepening of air distribution the combustion of the pulverized coal is also weakened, and the level of burnout is also reduced, so the air distribution cannot be deepened infinitely [21]. Bituminous coal has better burnout performance than lean coal, so the air distribution depth is high [22]. It can also be seen from Table 6 that, because bituminous coal is highly combustible, the CO concentration at the outlet of the cryogenic economizer does not change significantly with the reduction of excess

air after the adoption of staged combustion technology; however, the concentration of NOx decreased significantly. This can reduce the concentration of NOx and maintain high combustion efficiency.

Table 6. Test results of flue gas components at the exit of the economizer.

Serial Number	Name	Working Condition A-01	Working Condition A-02	Working Condition A-03	Working Condition B-04	Working Condition B-05	Working Condition B-06	Working Condition B-07
1	Oxygen (%)	3.95	4.00	5.05	3.03	2.60	2.43	3.49
2	CO concentration (ppm)	16.50	13.75	5.40	6.35	6.50	8.60	5.45
3	NOx concentration (ppm)	458.00	453.50	426.50	152.85	160.95	168.20	139.50
4	NOx concentration after conversion (mg·(Nm^3)$^{-1}$) (Dry basis, standard state, 6% oxygen)	866.50	862.00	865.00	275.30	283.45	293.05	257.80

From the above, the change in coal quality (lean coal to bituminous coal) and low-nitrogen combustion (using low-nitrogen burner and OFA technology) can greatly reduce NOx emissions concentrations.

5.4. Analysis of the Influence of Low-Temperature Economizer on Coal Consumption

A low-pressure economizer arranged after the air preheater, can use the waste heat of flue gas to heat the feed water, and can replace part of the low-pressure extraction steam, which can continue to work in the steam turbine, improving the efficiency of the system. When a low-pressure economizer was not used, the average temperature of the low-pressure economizer inlet flue gas was 146.68 °C, but when a low-pressure economizer was used, that decreased to 119.44 °C and 27.28 °C, respectively. The heat consumption of the steam turbine was reduced from 8159.40 kJ/(kW·h) to 8124.58 kJ/(kW·h) by heating the feed water with flue gas, and the total heat consumption rate was reduced by 34.82 J/(kW·h). After deducting the increased power consumption of the condensate pump caused by the input of the cryogenic economizer, the coal consumption was reduced by about 1.32 g/(kW·h), as detailed in Figure 4.

5.5. Comparative Analysis of Coal Consumption before and after Modification

The average coal consumption for the power supply after modification was 322.87 g/(kW·h), 9.83 g/(kW·h) lower than before modification; see Table 7 for details. The main reasons were:

(1) After the change of lean coal into high-volatile bituminous coal, the mechanical incomplete combustion loss of the boiler was greatly reduced, and the average value of q_4 for those two working conditions was only 0.747%; through the type modification of coal and economizers, the flue gas temperature of the boiler was reduced by 5.3 °C while the boiler efficiency increased by 2.35%, and the coal consumption decreased by 8.51 g/(kW·h).

(2) After the low-temperature economizer was put into operation, the heat consumption rate was reduced by 34.82 kJ/(kW·h). However, the rise in resistance in the condensate increased the power consumption of the condensate pump of the steam turbine, resulting in an increase of 0.02% in the auxiliary power rate of the plant, and after deducting the extra power consumption of the condensate pump from the power gain of the unit brought about by the installation of the low-temperature economizer, the coal consumption rate was finally reduced by 1.32 g/(kW·h).

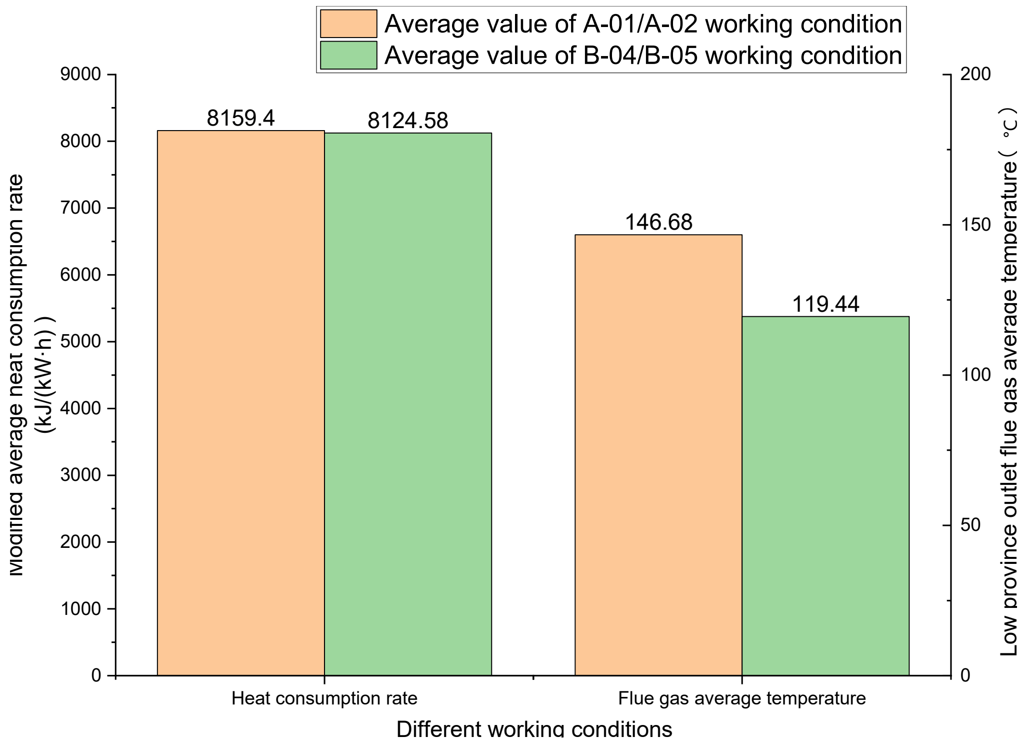

Figure 4. Average inlet flue gas temperature of low-pressure economizer and heat consumption in different working conditions.

Table 7. Comparison of coal consumption for power supply.

Name	Before Modification (After Fixing)	After Modification (After Fixing)	After Modification Minus Before Modification
Boiler efficiency at rated condition (%)	90.36	92.71	2.35
Heat consumption rate of turbine under rated conditions (kJ·(kW·h) $^{-1}$)	8159.40	8124.58	–34.82
The auxiliary power rate of plant under rated conditions (%)	5.978	5.973	–0.005
Pipeline efficiency in rated condition (%)	98.5	98.5	0
Coal consumption for power supply under rated, pure condensing condition (g·(kW·h)$^{-1}$)	332.70	322.87	–9.83

5.6. Analysis of Coal Conservation and Carbon Emission Reduction after Modification

(1) Coal conservation after renovation.

According to the provisions in the "Calculation of Main Energy Efficiency Indicators of Coal Power Units and Annual Energy Conservation" [23,24]:

The annual energy saving formed by energy consumption reduction = 5500 × rated power generation capacity × (1—the auxiliary power rate of the plant) × (coal consumption for power supply under pure condensing rated conditions before modification—coal consumption for power supply under pure condensing rated conditions after modification).

The rated power generation capacity was set to be taken from the nameplate of the power generation unit before the modification, and the capacity expansion factor was not considered. The power consumption rate of the plant was set to be that under the pure condensing rated condition after the unit is modified. The annual power generation equipment utilization hours of the unit was set to 5500.

The annual energy saving formed by the consumption reduction of the power generation unit = 5500 h × 330 MW × (1—5.973/100) × (332.70–322.87) g/(kW·h) = 16,775,780 kg standard coal = 16,776 tons of standard coal.

(2) Carbon emissions reduction after modification.

The formula for calculating the total amount of carbon dioxide emissions is as follows [25]:

$$G = M \times 2.4567 \quad (2)$$

where: G—the total amount of carbon dioxide emissions, t; M—the total energy consumption after converting various energy sources into standard coal, t; 2.4567—the value recommended by the Energy Research Institute of the National Development and Reform Commission, which means that the carbon dioxide emissions for 1 t standard coal is 2.4567 t.

The total amount of carbon dioxide emissions reduction formed by consumption reduction of the power generation unit = 2.4567 × 16,776 = 41,213.60 t.

6. Conclusions

(1) After the boiler was modified with bituminous coal and the installation of two, low-temperature economizers, the average boiler efficiency after the correction was 92.71%, 2.35% higher than the 90.36% before the modification (burning lean coal, after the correction). Under the coal quality and 250 MW load conditions, the measured thermal efficiency of the boiler was 92.55%, and the corrected thermal efficiency of the boiler was 92.51%. This is 2.58% higher than that loaded with 265 MW before the renovation (89.93%).

(2) The average NOx content in the flue gas at the economizer outlet (denitrification inlet) was 279.4 mg/Nm^3, when the two low-temperatures economizer were put into operation, which is about 68% lower than that of 864 mg/Nm^3 before the modification.

(3) After the boiler renovation, the average coal consumption for power supply after correction was 322.87 g/(kW·h), 9.83 g/(kW·h) lower than before the renovation. The modification of the pulverizing system and the major components of boiler reduced the coal consumption by 8.51 g/kW·h, and the addition of low-temperature economizers reduced the coal consumption rate by 1.32 g/(kW·h). The energy consumption reduction of the power generation unit brought about an annual energy savings of 16,776 tons of standard coal and a total carbon dioxide emissions reduction of 41,213.60 tons.

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