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Experimental study on optimization of over-fire air in modified combustion condition with selective catalytic reduction †

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Abstract

Recently, the use of NOx control retrofits is significantly increasing due to further tightening of regulations caused by worldwide environmental concerns. In order to reduce NOx emissions, most of the generators are equipped with SCR (Selective Catalytic Reduction) or OFA (Over-Fire Air) systems, while some generators being equipped with both systems. Here we present experimental evidence of higher boiler efficiency with efficient NOx control with consideration for influences on unburned carbon, under the condition that it should meet local and federal emissions requirements. The higher boiler efficiency has been achieved for a newly installed SCR system by optimizing OFA and reducing excess air quantity. The test was conducted over 6 months with a 500 MW coal-fired boiler. Stepwise closing of OFA dampers was carried out with and without simultaneous excess air optimization at a 500 MW nominal rating. We confirmed that our new operation leads to the following benefits: a) Reduction of UBC due to higher temperature in the furnace's main combustion zone, b) Improved fly-ash recycling ratio, c) Reduction of spray water into re-heater due to lower temperatures in the second (upper) combustion zone, and d) Reduction of exhaust gas loss. As a result, the boiler efficiency has increased by up to 0.4% and UBC (unburned carbon) has decreased by 0.8%. In conclusion, we confirmed that our new operation mode yields better boiler efficiency for newly installed SCR systems and mixed coal firing operating conditions.

Keywords: Air-staging; NOx retrofit; Over-fire-air; Selective catalytic reduction

1. Introduction

Since the Clean Air Act was amended in USA in late 1990s and early 2000s [1, 2], various technical options for reducing NOx emissions were researched. Most commonly used methods have been combustion modification (with re-burn or advanced re-burn), low NOx burner (LNB) coupled with over-fire air (OFA), selective non-catalytic NOx reduction (SNCR) and selective catalytic NOx reduction (SCR) [3-6]. The re-burn or advanced re-burn has limited applications due to its requirement to use natural gas. The SNCR has also limited application due to its size of units and ammonia slip. Therefore, the LNB (or LNB coupled with OFA) and SCR have been commercially viable options in most cases and widely used [7].

Furthermore, it has become inevitable that various kinds of coal, especially, low volatile matter coal, mixed coal and sub-bituminous coal are extensively used in the power plants even though the plants were originally designed to use bituminous coal. The main reason is due to unstable energy markets and ever-increasing coal prices. One of the most significant problems of using low quality coal is the environmental impact, or the increase of NOx emissions, which is one of the most tightly regulated emissions worldwide. This has led to significantly increased use of NOx control retrofits.

In the early 2000s the OFA, which is referred as an air-staging system, had been widely used for NOx control before the SCR technology was introduced in the commercial market [4]. It is common cases that the coal plants designed and built in late 1990s or early 2000s had installed OFA first and added SCR later on. Even though SCR is known to be efficient and commercially viable [5, 7-11], OFAs are still used in parallel with SCR without optimization of operation conditions due to the lack of confidence and experience in using SCR in parallel with OFA. It is obvious that OFA is inferior to SCR in terms of boiler efficiency because OFA produces more unburned fuel due to lower temperature in the main furnace to generate less NOx emissions. Therefore, it is also obvious that the role of OFA should be minimized when the more efficient SCR is appended in parallel with the existing OFA.

However, satisfying the national and inter-governmental environmental requirements related to NOx emissions in any

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circumstances is one of the most important objectives in power plant control, generation companies are mostly reluctant to change the control scheme for OFA even after the installation of SCR.

Considering this managerial conservativeness of the utility industry, it is therefore very important to have the physical evidence that how much the boiler efficiency can be improved quantitatively and how safely NOx emissions can be controlled when the role of OFA is minimized for the reduction of NOx emissions.

Here we present experimental results of how NOx can be controlled using both SCR and OFA when various types of coal are burned. And the result of the efficiency improvement is also presented with consideration for influences on the unburned carbon (UBC), under the condition of the national and inter-governmental environmental requirements.

Even though very limited amount of researches related to the SCR coupled with OFA can be found [6, 8], most of them are limited to the laboratory scale performance tests and only rough economical evaluations are given without physical experiments. Therefore, the main purpose of this paper is to show the experimental results to improve the efficiency of the pulverized fuel coal plant via optimizing excess air and OFA flow with newly installed SCR system. Main contributions of this paper are summarized as follows:

The experiments are performed on the optimization of excess air when both OFA and SCR are installed. They are conducted over 6 months with a 500 MW coal-fired power plant at the Korea's *Ha-Dong* thermal power plant.

Various types of coal, such as bituminous coal, low volatile matter coal, mixed coal and sub-bituminous coal, are used to increase the applicability of the result.

Brief economical impact of the proposed experimental results is analyzed.

This paper is organized as follows. Next section will describe the operation status and technical issues of the plant where the experiment is performed. Section 3 will explain the procedure of the experiment and its detailed results will be given in Section 4. The application of the study to the actual operation and a brief economical assessment are explained in Section 5. Conclusions will be given in the final section.

2. Operation status and technical issues

2.1 Operation status

As explained above, experiments are conducted at the 500 MW *Ha-Dong Thermal Power Plant* having once-through boiler. It was designed originally to fire bituminous coal, generating 1,700 tons of 541°C super-heated steam an hour [12, 13]. It should be noted that most of the coal-fired plants currently operating in Korea have very similar structures because they are built based on the standardized technology to reduce the operation and maintenance costs. Table 1 shows the list of the coal-fired plants in Korea which are using standardized technology and equivalent to the Ha-Dong plant. Therefore, the results of this study can easily be applied to other plants listed in Table 1 without significant modification. As shown in the last column of Table 1, most of the coal-fired plants rely on OFAs even though SCRs are installed.

Table 1.Standardized coal-fired plants in Korea.

Name	Unit MW	# of Units	Total MW	OFA Opening
BoRyoung #3-6	500	4	2,000	100%
SamCheonPo #5-6	500	2	1,000	50%
TaeAn #1-4	500	4	2,000	100%
Ha-Dong #1-6	500	6	3,000	80%
DangJin #1-6	500	6	3,000	70%
Total	-	22	11,000	

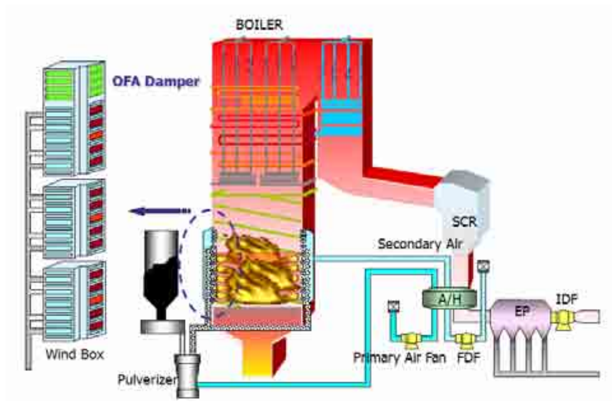

Fig. 1. A simplified structure of boiler system of *Ha-Dong* power plant.

A simplified diagram of boiler system installed in *Ha-Dong* power plant is shown in Fig. 1. As explained above, the OFA was originally installed to reduce and control the NOx emissions, but SCR has been installed later on. It is common practice to install a SCR De-NOx system to improve the environmental effects and meet the local regulations related to NOx emissions. For example, Ha-dong plant also installed the system in 2007 and having been emitting less than 70 ppm of NOx since then despite the fact that the local regulation for NOx emissions is 100 ppm.

2.2 Technical issues

More than 75% of the NOx formed during conventional PC (pulverized coal) firing is fuel NOx; the remainder is primarily thermal NOx. The most effective means of reducing fuel-based NOx formation is to reduce oxygen (air) availability during the critical step of de-volatilization [14, 15]. Additional air can then be added later in the process to complete char reactions and maintain high combustion efficiency [16, 17]. Oxygen availability can be reduced during de-volatilization in two ways. One method, referred to as air-staging, is to remove a portion of the combustion air from the burners and transfer it

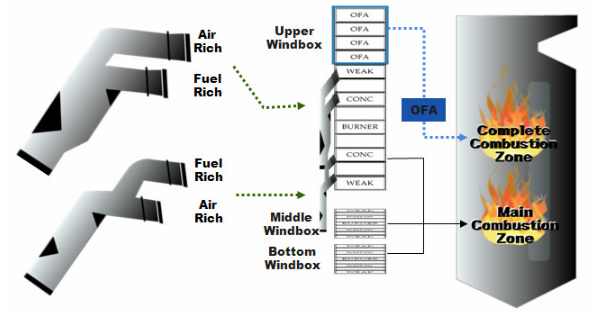

Fig. 2. Basic structure of boiler system with air-staging OFA.

through the OFA damper located just above the furnace burner. The basic structure of air-staging method is explained in Fig. 2. As most PC combustion systems typically operate with 20% excess air at their maximum firing rate, the *Ha-Dong* plant has the same operating conditions. The other method of reducing oxygen availability during coal de-volatilization is realized by the burner design known as PM (Pollution Minimum) burner. Ha-dong Thermal Power Plant adopts both methods. This burner was designed to supply all the combustion air into the flame, but limit its rate via burner nozzles. Only a fraction of the air is permitted to mix with the coal during de-volatilization. The remaining air is then mixed both downstream and upstream of the flame to complete combustion.

Therefore, for a power plant where OFA damper is installed, it is common practice to lower the temperature of main furnace to reduce the amount of NOx emissions. The *Ha-dong* plant, for instance, reduces the temperature by $200^{\circ}C$ to $1,400^{\circ}C$ compared with when there is no OFA damper. Due to this low temperature of the main furnace the amount of unburned fuel is increased. The loss from the unburned fuel is significant and the amount of over-fire air should be increased by 18-30%. It is significantly higher than the optimal value of 10-15% when the boiler efficiency is maximized.

Furthermore, due to the recent unstable supply of coal, most of generation companies started to use a mixture of various kinds of bituminous coal and sub-bituminous coal at a ratio of 20-80%. But the ratio of low quality coal usage grows gradually due to the skyrocketing international coal price. The UBC increases in fly-ash and consequently its recycling ratio decreases as a result of using such low-volatility coal. Firing various kinds of coal led to fairly severe temperature differences in the furnace's heating surfaces. Thus the control of boiler becomes significantly deteriorated and complicated. Use of high-moisture coal and low-calorie sub-bituminous coal lead to increased re-heater spray injection quantities, and higher exhaust gas temperatures and emissions cause low boiler efficiency. In addition, it is problematic because we operate in the same way even after installing the SCR De-NOx system. Comparisons of heat contents of the fuels used in *Ha-dong* Thermal are

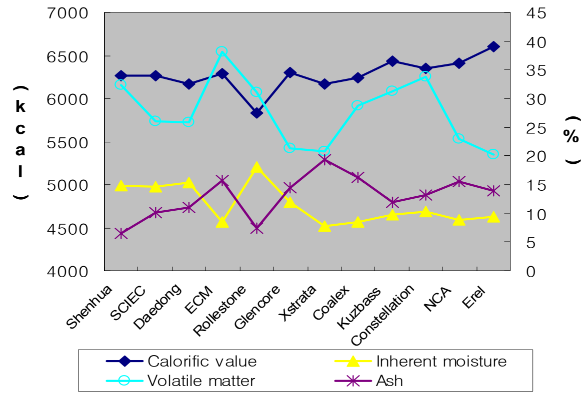

Fig. 3. Heat content analysis of the bituminous coal.

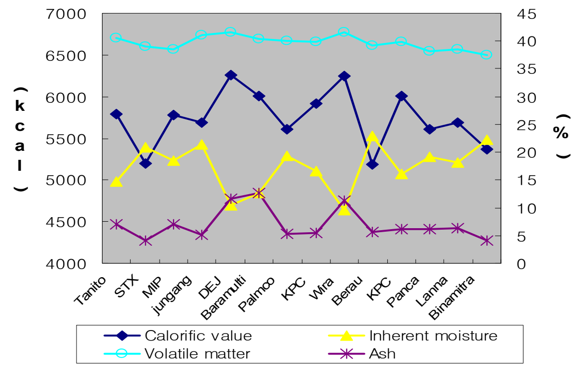

Fig. 4. Heat content analysis of the sub-bituminous coal.

shown in Figs. 3 and 4.

3. Description of experiment

The OFA system of *Ha-dong* plant consists of four air-staging dampers, which are controlled separately. Unfortunately the main control system does not have direct access to the damper actuators of OFAs. Therefore, it is the best way to adjust the openings of the dampers manually from the local control panels connected to the actuators.

In order to preserve safe operation of the plants, only 10% of opening is closed every five minutes. We made OFA flow smaller and smaller by measuring combustion characteristics and especially focusing on NOx emissions and UBC in fly-ash while excess air ratio was fixed. While OFA flow was fixed, NOx emissions were decreased by reducing combustion air by inches.

As mentioned above, all the experiments are performed based on the assumptions that the SCR is newly installed to the boiler system which the OFA has already been installed. Also the sub-bituminous coal is assumed to be burnt in the boiler system which was initially designed for bituminous coal firing. During the experiments, the effects on NOx emissions and UBC in fly-ash are also considered. In addition, these experiments have attempted to find better combustion condi-

Table 2. Various coals used in experiments.

Classification		Unit	Designed value	Average used in tests		
				Bituminous coal	Sub-bituminous coal	Ave.
Calorific value		kcal	6,080	6,265	5,735	6,000
Total moisture		%	10	10.91	17.46	14.19
Technical analysis	Ash	%	15	12.03	6.81	9.42
	Volatile matter	%	28	29.88	39.22	34.55
	Inherent moisture	%	5	3.88	11.66	7.77
	Fixed carbon	%	52	54.21	42.31	48.26
Elementary analysis	C	%	69	72.76	70.79	71.78
	H	%	4.3	4.14	4.82	4.48
	O	%	8.7	8.06	14.72	11.39
	N	%	1.4	1.59	1.31	1.45
	S	%	0.8	0.45	0.79	0.62
	Ash	%	15.8	12.46	7.57	10.02

tions for reducing exhaust gas loss; the most critical factor for boiler efficiency. After installation of SCR system, the existing OFA and excess air quantity have been optimized in terms of operation costs. Stepwise closings of OFA dampers were carried out with and without simultaneous excess air optimization, while generating a 500 MW nominal rating.

Combustion conditions were optimized to minimize exhaust gas loss; one of the most significant factors for boiler efficiency. This study was conducted for 6 months from February to July in 2007. Mixed coal at a ratio of 30-70% including 12 kinds of bituminous coal and 14 kinds of sub-bituminous coal was used during that period. In total, 8 types of mixed coal were used for the test: Shenhua + KPC, Shenhua + Wira, Glencore + KPC, Glencore + Berau, NCA + Tanito, Constellation + KPC, Constellation + Binamitra and Kuzbass + KPC. Same experiments are repeated three times for each type of coal. Average coal analysis is shown in Table 2.

4. Results of experiments

4.1 Optimal O_2 density

The first experiment performed is the full close of all four OFA dampers to verify that it is possible to control the NOx emissions only by SCR with OFA fully closed. The procedure of experiment and its result are summarized in Table 3 and 4, respectively.

As shown in Table 4, simple closing of OFA without adjustment of excess air shows not only positive results but also some negative results such as the increase of NOx emissions and ammonia consumption, which are mostly due to excess air injected into the main furnace. Therefore, more careful control of excess air should be performed.

After closing OFA dampers, further experiments are performed to find the optimal condition of excess air which maximizes the boiler efficiency. We gradually reduce the O_2 density from 3.6% (O_2 density when all four OFA dampers are fully open) to 2.2%, and found the plant efficiency is maximized when the O_2 density is 2.5%. The procedure of experiment is briefly explained in Table 5.

Table 3. Experiment procedures (Full OFA close).

Hours	Experiment	Note
2	Data acquisition with OFA open	2 times
1	Full close of OFA – 1,2,3,4	4 (upper) 1 (lower)
2	Output stabilization	
6	Data acquisition with OFA full close	3 times
1	Full open of OFA – 1,2,3,4	1 (lower) 4 (upper)

Table 4. Experiment result (Full OFA close).

Positive results	Negative results
• Water separator outlet temperature increase by 6℃ • Primary RH outlet temperature decrease by 5℃ • RH spray flow decrease by 3.2T/h • GAH inlet gas temperature decrease by 4℃ • Ash unburned coal decrease by 0.96%	• NOx emissions increased by 34ppm • Ammonia consumption increased by 23kg/h

Table 5. Experiment procedure (O_2 density adjustment).

Experiment	Hours	Procedure
1st Adjustment	3	Decrease air/fuel ratio to 0.91 (O_2 density: 3.0%)
	2	Output stabilization
	2	Data acquisition (3 times)
i^{th} adjustment	3	Air/fuel ratio adjustment to 0.87 (O_2 density: 2.5%)
	2	Output stabilization
	2	Data acquisition (3 times)

4.2 Results of experiments

4.2.1 Furnace temperature changes

Temperature changes at several points in the furnace are shown in Table 6 and Fig. 5. Steam temperature in the water separator outlet (3rd column of Table 6) and super heater outlets (4th-6th columns) increases while that of the primary reheater tube outlet (7th column) decreases. Thus, super heater spray flow increases and re-heater spray flow decreases. Due to OFA reduction, air-staging function has no effect and most of the combustion activity occurs inside the main burner zones. The higher temperature and lower combustion air helps water walls absorb more heat because combustion gas at the same weight absorb more heats. As a result, the temperature de-

Table 6.Temperatures in the furnace by combustion condition.

Conditions		Temp. on heating surface						Temp. on exhaust gas		Spray flow ton/hr	
OFA	O_2	WS	PSH	SSH	FSH	PRH	FRH	Eco.	GAH	SH	RH
15.5%	3.6%	416	464	515	542	451	542	342	129	96	21
1.3%	3.6%	421	469	518	541	448	542	339	127	102	12
1.3%	2.5%	422	470	518	541	445	542	334	123	104	8

OFA : The proportion of OFA in total combustion air (15.5%: damper full opened, 1.3%: full closed).

O_2: Discharge density of O_2 in exhaust gas.

** Tested coal is mixture of 60% Constellation (from Australia) and 40% KPC (from Indonesia)

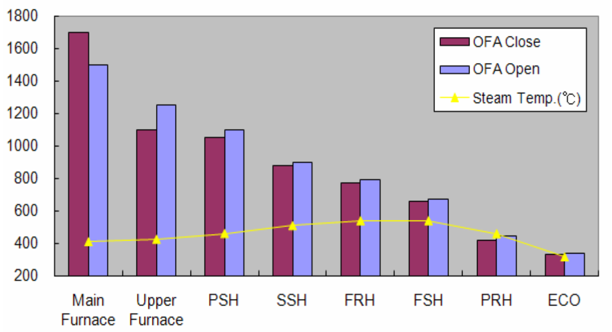

Fig. 5. Temperature changes in the furnace.

creases in the upper area of the furnace, and increases in the exhaust gas. From this, it is confirmed that adjusting OFA and combustion air improves boiler control when firing various kinds of coal.

4.2.2 NOx and unburned carbon (UBC)

Fig. 6 shows that NOx and UBC production changes according to OFA flow control. When the OFA ratio is changed from 15.5% (original operating value when OFA is fully open) to 1.3% (OFA is fully closed) with a fixed quantity of excess air, NOx increases drastically and UBC decreases slightly. Though this result is caused by disabling the PM burner and air-staging function, NOx emissions are still within a manageable range under the SCR system. As OFA reduces, combustion quantities increases due to abundant air availability, as a result of high furnace temperatures, UBC decreases and NOx increases. At OFA of 15.5% (full open), the trends for NOx and UBC are shown in Fig. 7-A, when O_2 in the exhaust gas changes from 3.6% to 2.2%. When reducing excess air, NOx slightly decreases, but UBC increases rapidly. Fig. 7-B shows that NOx and UBC curves as a function of O_2 control at 1.3% of OFA (full close). NOx increases at 3.6% of O_2. However, its value is not much higher than the value in 15.5% of OFA with 3.6% of O_2 when O_2 reduces to 2.2%, and UBC slightly increases.

The amount of UBC produced is considerably dependent on the types of coal, which is as shown in Table 7. The amount of UBC decreases by 0.96% in average by the OFA close and

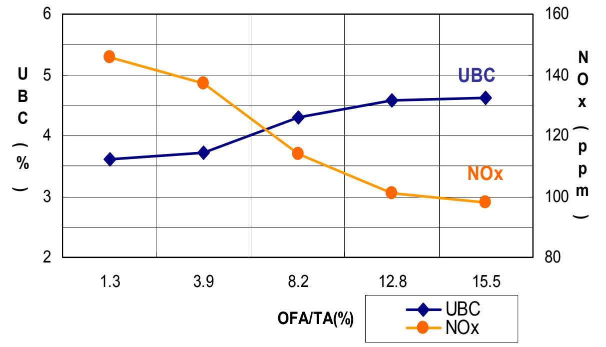

Fig. 6. UBC and NOx vs. OFA.

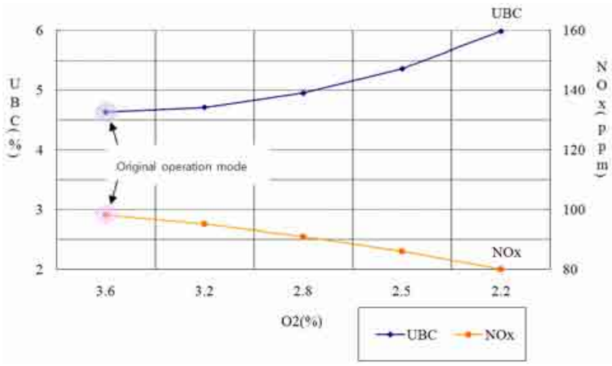

Fig. 7-A. UBC and NOx vs. O_2 at 15.5% OFA.

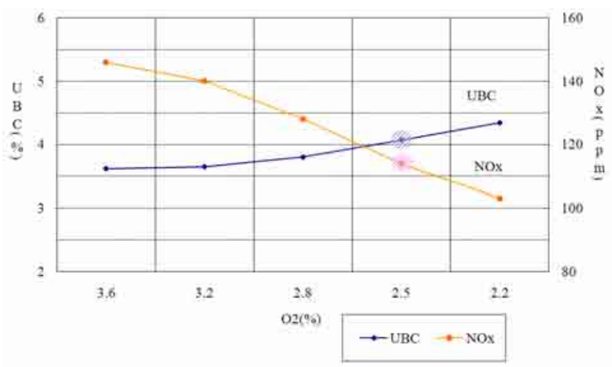

Fig. 7-B. UBC and NOx vs. O_2 at 1.3% OFA.

excess air optimization. The amount of UBC is inversely dependent on the volatility of the coal. The main reason why the amount of UBC is decreased when the OFA is closed is because the combustion speed increases with higher temperature in the main furnace. It is commonly known that the combustion speed of fuel increase 2-3 times faster whenever the temperature increase by 10$^\circ C$ [13]. As shown in Table 7, whatever type of coal is burned, the amount of UBC is decreased by the excess air optimization, and hence the boiler efficiency is improved.

4.2.3 The amount of RH spray water

The amount of RH spray water is one of the factors which affect turbine or plant efficiency. RH spray water is injected through extraction nozzle of the mid-pressure stage of feed-

Table 7. The amount of UBC by coal types.

Coal	Measured amount of UBC [%]			
	OFA open	OFA Closed	Excess Air Optimized	Difference
Shenhua + KPC	3.05	2.95	2.34	-0.71
Shenhua +Wira	2.34	2.03	1.80	-0.54
Constellation +KPC	6.15	4.52	4.78	-1.37
Constellation +Binamitra	5.20	4.62	3.73	-1.47
Glencore +KPC	4.39	2.94	3.38	-1.01
Glencore +Berau	5.53	4.68	4.86	-0.67
Kuzbass +KPC	5.77	5.34	5.34	-0.63
NCA +Tanito	9.81	7.32	7.32	-1.27
Average	5.28	4.30	4.32	-0.96

Table 8. The amount of RH spray water by coal type.

Coal	Measured amount of UBC [ton/hour]			
	OFA open	OFA Closed	Excess Air Optimized	Difference
Shenhua + KPC	12.5	3.8	3.6	-8.9
Shenhua +Wira	4.0	2.3	1.9	-2.1
Constellation +KPC	21.3	16.7	10.3	-11.0
Constellation +Binamitra	12.2	9.9	7.4	-4.8
Glencore +KPC	5.2	3.3	3.0	-2.2
Glencore +Berau	4.3	3.5	3.0	-1.3
Kuzbass +KPC	3.4	2.7	2.4	-1.0
NCA +Tanito	10.7	5.8	4.9	-5.8
Average	9.2	6.0	4.6	-4.64

Table 9. Exhaust gas loss measurement.

Coal	Loss from exhaust gas [%]			
	OFA open	OFA Closed	Excess Air Optimized	Difference
Shenhua + KPC	3.83	3.72	3.63	-0.20
Shenhua +Wira	3.78	3.69	3.61	-0.17
Constellation +KPC	3.88	3.78	3.66	-0.22
Constellation +Binamitra	3.81	3.73	3.65	-0.16
Glencore +KPC	3.80	3.68	3.59	-0.21
Glencore +Berau	3.78	3.65	3.56	-0.22
Kuzbass +KPC	3.87	3.65	3.63	-0.24
NCA +Tanito	3.72	3.62	3.55	-0.17
Average	3.81	3.69	3.61	-0.20

Table 10. The amount of ammonia consumption.

Coal	Ammonia consumption [kg/hour]			
	OFA open	OFA Closed	Excess Air Optimized	Difference
Shenhua + KPC	46.2	67.2	48.2	+2.0
Shenhua +Wira	46.5	67.0	45.8	-0.7
Constellation +KPC	62.9	80.7	61.5	-1.4
Constellation +Binamitra	59.7	71.7	56.3	-3.4
Glencore +KPC	87.1	11.40	91.4	+4.3
Glencore +Berau	50.5	90.0	64.5	+14.0
Kuzbass +KPC	82.0	109.3	75.0	-7.0
NCA +Tanito	79.8	102.2	72.6	-7.2
Average	64.3	87.8	64.4	+0.07

water pump which is located in front of high-pressure feed-water heater, so it reduces the extraction efficiency. If the amount of RH spray water is decreased by 1.0 ton/hour, plant efficiency is known to be increased by 0.0065% [13].

The amount of RH spray water measured during the experiments is summarized in Table 8. It reduces by 3.2 ton/hour in average when OFA is closed due to low temperature in the RH. It is further reduced by 1.44 ton/hour after the excess air is optimized. In total 4.64 ton/hour of RH spray water is reduced based on the experiment results.

4.2.4 The amount of exhaust gas

The amount of exhaust gas measured during the experiments is shown in Table 8. As the result, the amount of air flow reduces by 37kg/sec, which is equivalent to 0.2% of loss reduction.

4.2.5 The amount of ammonia consumption

The amount of ammonia consumption is shown in Table 10. As explained earlier, the amount of ammonia consumption is significantly increased due to OFA close, but it recovers to almost similar level of the original condition when the OFA is fully open. However, further study is required for the case of Glencore coal where the amount of ammonia consumption is significantly increased.

4.3 Calculation of efficiency improvement

As explained above, the efficiency of plant is notably improved. The improvement of efficiency consists of two parts: 1) boiler efficiency improvement due to reduction of unburned fuel and exhaust gas, 2) the reduction of RH spray water injection.

Efficiency improvement from the reduction of unburned fuel is about 0.18% calculated as follows:

$$= \frac{Calorie\ of\ carbon \times Ash\ content\ rate \times \dfrac{rate\ of\ UBC}{1 - rate\ of\ UBC}}{Calorie\ of\ coal} \times 100$$

$$= \frac{8{,}056 \times 0.14 \times 0.0096 / (1 - 0.0096)}{6{,}080} \times 100$$

$$= 0.18\%$$

whereas the boiler efficiency improvement from the exhaust gas reduction is 0.2% as explained in the previous section. All together, the boiler efficiency improvement is 0.38%. This improvement of boiler efficiency will improve the overall plant efficiency by 0.17% because the efficiency of the turbine is about 46.0% (the overall plant efficiency is about 39.7%).

If the plant efficiency improvement of 0.03% due to the reduction of RH spray water is added to the above number, then the overall plant efficiency improvement reaches about 0.2%. This efficiency improvement let us save about 7,000 ton of coal a year per each unit.

Table 11. Operation modes according to the fuel conditions.

Operation Mode	UBC ratio	Air/Fuel Ratio	O2 density	Notes
Efficiency Mode I	Below 4%	0.87-0.89	2.5-2.8	
Efficiency Mode II	4-6%	0.91-0.93	2.9-3.2	
UBC Control Mode I	6-8%	0.94-0.96	3.3-3.6	
UBC Control Mode II	Above 8%	-	-	Unrecommend-able

Fig. 8. Operator monitor with re-heater temperature difference.

5. Application to operation

5.1 Optimized condition for boiler efficiency

We confirmed that the condition of 2.5% of O_2 in exhaust gas finds most cost-effective operation mode with consideration of ash recycling by following observations. First, the lower O_2 discharge density draw the higher the boiler efficiency increases. Second, changes are not much below 2.5% of O_2, but UBC increases noticeably.

5.2 Operation for combustion conditions

Before we modified operation standards, there had been not much measures but just controlled SH & RH spray and feed water flow over the problem like temperature differences in furnace's heating surfaces shown in Fig. 8. Combusting mixed coal (more than 40 types) are changing everyday in Ha-dong Thermal Power Plant. The use of diverse characteristic mixed coals raise furnace's various combustion problems. Thus, the optimized condition at 1.3% of OFA and 2.5% of O_2 has been used for standard operation. However, when problems occur, such as too low Final re-heater temperatures (below 530°C), too high concentration in inlet NOx (over 130ppm) and too high water separator temperatures, we increase supply air via OFA. In case over 6% of UBC, we increase total supplying combustion air. Fig. 8 represents one of the temperature difference problems caused by changing combusting coals.

5.3 Economic evaluation of the results

The improvement of 0.2% in plant efficiency would reduce the coal consumption by about 7,000 metric ton, which is equivalent to about 560,000 US$ according to the current international coal price of US$ 80/ton. Also it reduces the CO_2 emissions by about 15,000 CO_2 ton.

As shown in the Table 1, there are 21 other similar plants in Korea where the proposed method can be directly applied. Hence, we can reduce the coal consumption by about 140,000 metric tons from all 22 plants, which is equivalent to 12 million US$ a year.

5.4 Operation mode

Based on the results of the experiments, the role of OFA can be significantly reduced as the NOx reduction retrofit. The OFAs can be used only when the emergency state. We carefully decide that the lower two dampers of OFA (OFA #1 and #2) will be open only when the outlet temperature of final re-heater becomes below 530 $^\circ C$.

Furthermore, the operation modes should be more carefully chosen according to the ratio of unburned carbon in the fuel, which is summarized in Table 11.

6. Conclusions

It is a challenging goal to optimize operating conditions caused by firing sub-bituminous coal in boilers designed for bituminous coal. This study focused on OFA and excess air rates, primarily considering NOx emissions and unburned carbon in ash, and attempted to confirm better boiler efficiency through optimizing combustion conditions.

The test was conducted over 6 months with a 500 MW coal-fired boiler at Korea's Ha-dong thermal power plant. Stepwise closing of OFA dampers was carried out with and without simultaneous excess air optimization, while generating a 500 MW nominal rating.

We confirmed that our new operation leads to the following benefits: a) Reduction of UBC due to higher temperature in the furnace's main combustion zone, b) Improved fly-ash recycling ratio, c) Reduction of spray water into re-heater due to lower temperatures in the second (upper) combustion zone, d) Reduction of exhaust gas loss. As a result, the boiler efficiency has increased by up to 0.4% which is calculated with decreased UBC by 0.8%.

In conclusion, we re-confirmed that our new operation mode yields better boiler efficiency in modified combustion conditions, such as the newly installed SCR system and during the use of low quality coal.

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Nomenclature

Eco : Economizer
FRH : Final re-heater
FSH : Final super-heater
LNB : Low NOx burner
OFA : Over-fire Air
PRH : Primary re-heater
PSH : Primary super- heater, SSH: Secondary super-heater
RH : Re-heater
SCR : Selective catalytic reduction
SNCR : Selective non-catalytic reduction
SH : Super-heater
UBC : Unburned carbon
WS : Water separator

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