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Unburned carbon fraction with operation variables in a commercial circulating fluidized bed boiler during co-combustion of various anthracites

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Abstract−Reduction of unburned carbon fraction in exhaust during co-combustion of various coals in a circulating fluidized bed boiler (CFB) is required to save energy loss and to optimize coal utilization as well as to improve the boiler efficiency. In this study, the effects of operation variables such as coal, air and heat flow rates, co-combustion ratio of each coal, primary to secondary air ratio on unburned carbon fraction were analyzed and evaluated in two units of 200 MWe circulating fluidized bed boiler in the Tonghae thermal power plant. From the results, the comprehensive correlation among unburned carbon fraction and operation variables in #1 and #2 units of the CFB boiler could be derived with a good agreement. This would be expected to give a good guideline to reduce the unburned carbon content in exhaust in the CFB boiler.

Key words: Unburned Carbon, Operation Variables, CFB, Co-combustion, Tonghae Thermal Power Plant

INTRODUCTION

There has been increased interest in achieving effective coal utilization and maximizing efficiency of a thermal power plant in Korea as well as diversifying fuels, as the Korean electric power generation industry is largely dependent on imported fuels. Moreover, the prices of coal and oil are increasing as the world economy is showing signs of recovery. Also, the imbalance between supply and demand of high-quality coal requires taking measures for effective fuel utilization.

One of the successful technologies for energy utilization is a circulating fluidized bed (CFB) combustion technology because of its capability of firing various fuels such as a large range of coals, biomass, sludge and wastes [1-3]. So, the construction and operation of the CFB boiler has been increased in Korea as shown in Table 1. The CFB technology in the electric power generation industry shows a trend toward boilers with larger capacity and co-firing low-quality coal with other fuels such as another grade coals, refuse derived fuel (RDF) and biomass [4,5]. However, the combustion of the lower quality coals, which include high moisture or high ash coals, often causes increase of unburned carbon fraction in exhaust because of the decrease of the fuel reactivity and imbalance of heat flow in the furnace [6,7].

On the other hand, Korea East West Power Company, which is one of the subsidiaries of Korea Electric Power Corporation (KEPCO), constructed two units of the Tonghae CFB boiler (2×200 MWe) in 1998 and 1999, and has been operating them. The operation has been successful even though the boilers use Korean anthracite, which is a known low-quality fuel owing to its low heating value, high ash content, and low combustion reactivity [1,5,8]. However, the high content of unburned carbon in exhaust during combustion of this type of lower reactivity coals was one of the problems in the Tonghae CFB boiler. Consequently, it also caused a raising of the temperatures of the furnace exit and the cyclones due to enhancement of post-combustion of the fine carbon particles, resulting in lowering the desulfurization efficiency and operation stability in the CFB boiler [1,8,9].

Therefore, it is required that the unburned carbon fraction from the CFB boiler be reduced at adjustable operation ranges in the commercial CFB boiler without any risk. In this study, the sensitivity of operational variables affecting the unburned carbon fraction has been analyzed and evaluated in the commercial Tonghae CFB boiler. This can be attributed to operating the CFB boiler effectively and can also give the optimum operational guide to reduce the unburned carbon in the CFB boiler.

EXPERIMENT

1. Features of the Tonghae CFB Boiler

The Tonghae CFB boiler, which has been described in many previous studies, is shown in Fig. 1 [1,4,5,7-9]. It consists of a furnace (19 m-W×8 m-L×32 m-H), three cyclones and loopseals, three fluidized bed heat exchangers (FBHEs) and a fluidized bed ash cooler (FBAC). The furnace of the CFB has a rectangular footprint which allows for good fuel mixing. Limestone is injected with the fuel feed chutes in two injection ports along the rear wall. Bottom ash is removed from the furnace via two ash control valves (ACV) and then is introduced into an FBAC. The loopseals serve to create a pressure seal from the positive pressure in the combustor to the negative pressure in the cyclone. This pressure seal prevents the flow of material back up the cyclone from the bottom of the combustor. The loopseal is a compact, low-velocity multi-chamber fluidization grate. In the Tonghae CFB unit, the boiler turndown requirement, coupled with the difficulty of burning anthracite fuel, resulted in FBHEs. At each of the three loopseals, a stream of the solid materials is diverted and introduced into an FBHE. The FBHEs are bubbling beds, containing natural circulation evaporative, superheat and

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Table 1. Status of CFB boilers in Korea (2010)

Company/Location	Year	Capacity (Steam)	Steam Pr. (kg/cm^3)	Fuel	Category	Supplier/Design
Oriental Chemical/Incheon	1984	120	110	Bit. Coal	Co-Gen	Hyundai HI[a]/Ahlstrom
SK/Suwon & Ulsan	1988/ 1989	25/ 200	10/ 114	Bit. Coal	Co-Gen	Hyundai HI/Ahlstrom
LG/Yeocheon	1989	210	102	Bit. Coal	Co-Gen	Hyundai HI/Ahlstrom
Hyundai Oil/Daesan	1989	120	110	Coke	Co-Gen	Hyundai HI/Ahlstrom
Petrochem. Service Co./Ulsan	1990	250	93	Bit. Coal	Co-Gen	Hyundai HI/Ahlstrom
Dyeing Complex/Busan	1991	160 (80×2)	102	Bit. Coal	Co-Gen	Daewoo HI
Korea Energy/Onsan	1991	175	115	Bit. Coal	Co-Gen	Doosan/Lurgi
Sam Yang GENEX/Incheon	1990	60	63	Bit. Coal	Co-Gen	Hyundai HI/Ahlstrom
EWP/Tonghae	1998/ 1999	693×2	176	Anth./RDF	Electric	Doosan/Alstom
Kumho Petrochem./Yeosu	2003	305	100	Bit. Coal	Co-Gen	Hyundai HI
Dyeing Complex/Daegu	2004	160	92	Bit. Coal	Co-Gen	Hyundai HI
Gunjang Energy/Gunsan	2007/ 2010	200×2/ 250	93/ 95	Sub.bit. Coal	Co-Gen	Hyundai HI
Hanhwa Petrochem./Yeosu	2009	400×3	93	Sub.bit. Coal	Co-Gen	Foster Wheeler
BASF/Gunsan	2009	180	45	Sub.bit. Coal	Process	Hyundai HI
Gunjang Ind. Complex Cogen./Gunsan	2011	250×2	120	Sub.bit. Coal	Co-Gen	Hyundai HI
SEETEC/Daesan	2011	500	95	Sub.bit. Coal	Co-Gen	-
KOSEP/Yeosu	2011	1040	176	Sub.bit./brown Coal	Electric	Doosan
KOSPO/Samchuk	2015	1300×2	260	Sub.bit/brown Coal	Electric	Foster Wheeler

[a]HI: heavy industries

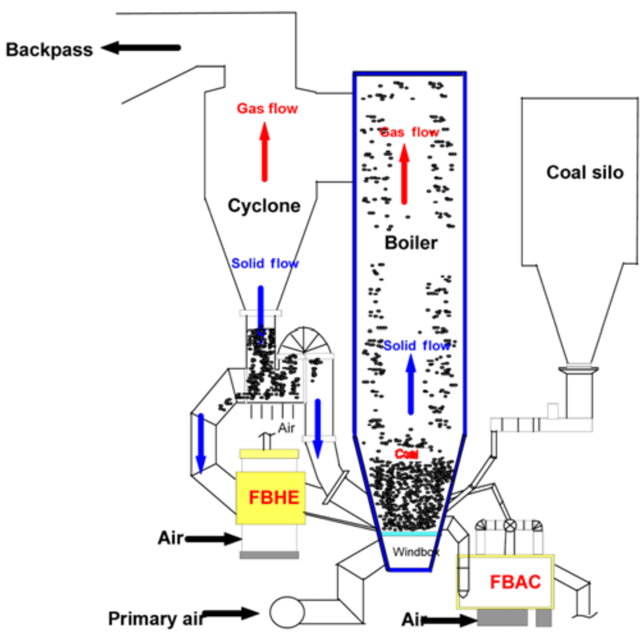

Fig. 1. Tonghae CFB boiler feature.

reheat heat transfer surfaces. As the solids from the loopseals flow over and through the FBHE heat transfer surfaces, the solid particles are cooled and then returned to the combustor. Some of the fine particles which are entrained and not captured by cyclones are collected by an electrostatic precipitator. These fine particles are reserved in ash silos and then are disposed to the ash pond or are reused in cement materials like bottom ash particles.

2. Experimental Conditions

The characteristics of unburned carbon content at various operation conditions such as air flow rate, co-combustion ratio of coals, coal flow rate and its heating value, and primary and secondary air ratio were analyzed and evaluated at a constant power generation condition of the CFB boiler. The range of operation conditions adapted in this study is shown in Table 2. The #1 and #2 units of the Tonghae CFB boiler were operated at the same conditions for 21 days; then, additional experiments were carried out for 36 days in #2 unit of the CFB boiler through the extension of operation conditions.

Pressures along the combustor were measured at 0.9 m (P1), 5.2 m (P2), and 28.5 m (P3) above the distributor and in the windbox (P0). The pressure drop in the upper part was the difference between P2 and P3, and the difference between P0 and P3, total pressure drop, was kept at a constant value via controlling the ACV of the furnace. Temperatures of the combustor were measured at 0.75 m (furnace's lower part), 5.65 m (furnace's upper part), and 28.4 m (furnace exit) above the distributor. At each point, six different horizontal temperatures were measured and averaged. The temperatures of three cyclones exits were also measured separately and averaged. For the temperature measurement, K-type thermocouples were used with an accuracy of ±0.1% of actual span encountered. Also, the thermocouples and compensating lead wire complied with the International Society of Automation (ISA) standard. The pressures were measured by pressure transmitters with an accuracy of ±1.0% of

Table 2. Operation conditions of the Tonghae CFB boiler

Conditions	Unit 1	Unit 2
Power generation [MWe]	193.3-199.2	195.9-200.6
Total coal flow rate [t/h]	94.2-109.7	89.2-105.2
KD coal flow rate [t/h]	2.5-22.6	0-60.9
NK coal flow rate [t/h]	2.9-33.1	0-107.5
VN coal flow rate [t/h]	53.0-99.2	0-97.5
KD coal ratio [%]	3.1-26.5	0-71.5
Coal size [mm]	<8 mm	<8 mm
Input heating value [kcal/kg]	4,663-5,286	4,576-5,670
Total air flow rate [kg/s]	171.1-180.2	171.0-186.9
Primary air flow rate [kg/s]	82.6-87.1	82.6-90.9
Secondary air flow rate [kg/s]	52.6-57.6	52.4-61.7

Table 3. Analyses of coals used in this study

Component		KD coal	NK coal	VN coal
Proximate analysis (air dry basis) [wt%]	Moisture	4.10	1.92	1.70
	Volatile matter	7.30	9.09	9.92
	Fixed carbon	56.16	75.79	51.35
	Ash	32.44	13.20	37.03
Ultimate analysis (dry, ash free basis) [wt%]	C	95.44	95.85	92.50
	H	1.10	1.01	3.94
	O*	2.18	2.56	1.56
	N	0.42	0.06	1.27
	S	0.86	0.52	0.73
Ash analysis [wt%]	SiO_2	53.31	58.67	56.70
	Al_2O_3	31.72	26.47	28.74
	Fe_2O_3	4.79	4.69	4.95
	TiO_2	1.65	1.46	0.88
	CaO	0.76	1.13	0.50
	MgO	0.61	0.70	1.08
	Na_2O	0.27	1.13	0.31
	K_2O	3.63	5.09	5.24
	SO_3	0.27	0.28	0.31
	etc	2.99	0.38	1.29
Heating value (air dry basis) [kcal/kg]		4,816	6,315	4,953
IDT [°C]		1,450	1,230	1,455

full scale. All data from the CFB boiler such as temperatures, pressures, air and limestone flow rates and emissions of SO_2 and NO_x were measured at one second intervals for two hours twice a day and were averaged. In addition, it was initially assumed that all measuring instruments of #1 and #2 units of the CFB boiler had the same degree of the accuracy and errors.

Korean anthracite (KD coal), which is Kyong-dong coal produced in Kang-Won Province, Korea, North Korean anthracite (NK coal) and Vietnamese anthracite (VN coal), which is imported from North Korea and Vietnam, respectively, were used as fuels and their analyses are shown in Table 3. As shown in the table, NK coal has a lower ash content and a higher fixed carbon content compared with KD coal, which is the design coal of the Tonghae CFB boiler. Also, the amount of S is lower, and Ca content is higher relatively. VN coal has high content of volatile matter but low CaO in the ash. The heating values of the coals are in the range of 4,861-6,315 kcal/kg, so the coal flow rate was changed automatically to keep a constant power generation, relevant to co-combustion ratio of each coal.

The content of unburned carbon was determined by analyzing the carbon content in fly and bottom ashes, respectively, after considering the ratio of fly to bottom ashes which could be taken as 47.5 : 52.5 relevant to an annual operation average.

RESULTS AND DISCUSSION

1. Effect of Coal Flow Rate and Species

The effects of coal flow rate and heating value on unburned carbon fraction in #1 and #2 units of the CFB boiler are shown in Fig. 2. Despite a nearly constant power generation of 200 MWe in the operation conditions, the coal flow rate was changed due to the change of coal species and its co-combustion ratio, and heating value of the mixed coal. Moreover, air flow rate was also varied to meet a desired excess air ratio depending on the coal flow rate in the commercial CFB boiler. So, all data from these commercial scale experiments were necessarily coupled with each other. As shown in Fig. 2(a) and (b), unburned carbon fraction showed a slightly increasing trend with an increase of coal flow rate in both units of the CFB boiler. When the heating value of the coal fed into the boiler increased, the unburned carbon fraction decreased slightly in #2 unit and did not change appreciably in #1 unit as shown in Fig. 2(c) and (d). This may be the reason that the residence time of fine particles in the furnace decreased due to increased air flow rate, which was controlled to meet a required excess air balance depending on the increase of coal flow rate and the decrease of coal heating value. However, the change of unburned carbon with variation of coal flow rate and heating value in #1 unit was comparatively lower than that in #2 unit. This is indicative of a little influence of coal flow rate and heating value on the content of unburned carbon in #1 unit.

Fig. 3 shows the effect of coal flow rates of KD, NK and VN coals on unburned carbon fraction. The unburned carbon fraction was on a decreasing trend with an increase of KD coal flow rate, on an increasing trend with NK coal flow rate and did not change appreciably with variation of VN coal flow rate in #1 unit of the boiler (Fig. 3(a), (c), (e)). In the case of #2 unit, as shown in Fig. 3(b), (d) and (f), the unburned carbon fraction showed different trends. It increased as KD and NK coal flow rates increased but decreased with increase of VN coal flow rate. This implies that each unit seemed to be operated differently although the operation conditions of both units were kept at the same values. As a result, the unburned carbon fraction of each unit seemed to be affected differently despite the same variations of the operation conditions.

2. Effect of Air Flow Rate

The change of air flow rate in the CFB boiler causes changes of excess air ratio and gas velocity of the furnace. Fig. 4 shows the effects of total, primary and secondary air flow rates on unburned carbon fraction of the CFB boiler. As total, primary and secondary air flow rates of both units of the CFB boiler increased, the unburned carbon fraction showed a decreasing trend. Especially, it could be observed clearly in #1 unit of the CFB boiler as shown in Fig. 4(a),

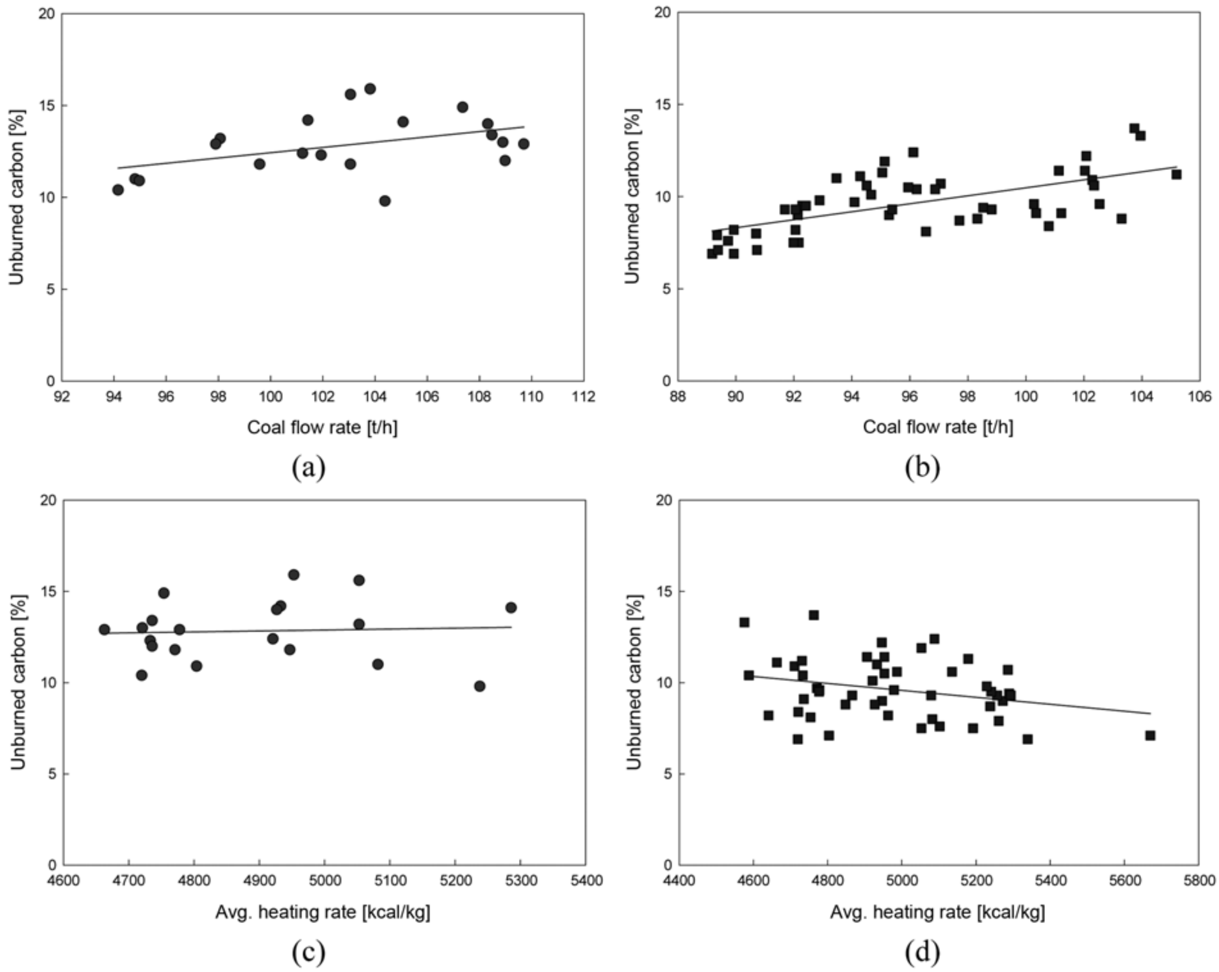

Fig. 2. Effect of total coal flow rate and its heating value on unburned carbon fraction: (a) and (c) #1 unit, (b) and (d) #2 unit.

(c) and (e). This implies that unburned carbon fraction in the furnace of #1 unit was more influenced by a change of excess air ratio rather than by a change of gas velocity affecting the residence time of fine particles when the air flow rates in the furnace increased.

Unburned carbon fraction with oxygen concentration of a stack of the CFB boiler is shown in Fig. 5, in which the oxygen concentration represents the residual quantity of oxygen after combustion reaction in the boiler relevant to excess air ratio. The unburned carbon fraction certainly increased as the oxygen concentration increased in the range of 1.5-2.5% in #1 unit, but in the case of #2 unit the unburned carbon fraction did not change appreciably with an increase of oxygen concentration in the range of 3.6-5.3%. From the results of Figs. 4 and 5, the following can be considered. First, the increase of excess air ratio relating to oxygen concentration of the stack could contribute to a significant decrease of unburned carbon fraction because of lack of oxygen in the actual operation condition of #1 unit of the CFB boiler. So the increase of air flow rate in #1 unit of the CFB boiler could supply the increase of excess air ratio and then could reduce the unburned carbon fraction. Second, unburned carbon fraction did not change appreciably with the increase of oxygen concentration in #2 unit because excess air ratio was already large enough. So the increase of airflow rate in #2 unit just increased oxygen concentration at the stack of the CFB boiler without reduction of the unburned carbon fraction. This signifies that air flow rate of #1 unit was less than that of #2 unit although the operation conditions of both units were kept at the same values. Consequently, the measuring system of air flow rate in #1 unit seemed to indicate a larger value than actual one, so it needs to be inspected and corrected. However, the effects of operation variables on unburned carbon fraction in #1 unit were analyzed and evaluated continuously herein because the changes of data from #1 unit could be regarded as important results in spite of the above fault.

3. Change of Temperature and Pressure Drop with Unburned Carbon Fraction

Fig. 6(a) and (b) show a change of temperatures of the furnace and cyclone exits in #1 and #2 units of the CFB boiler with unburned carbon fraction. Many previous studies have reported that the temperature of the furnace and cyclone exits of the Tonghae CFB boiler varied with fuel properties such as combustion reactivity and particle size distribution, although the lower bed temperature of the furnace was kept at a nearly constant of 880 °C [1,5]. In this study, the furnace exit temperature of #1 unit and the cyclone exit temperature of #2 were shown to increase with an increase of unburned carbon fraction. This could be observed in the Tonghae CFB boiler as high content of unburned carbon in flue gas, which resulted from low combustion reactivity of coal, was re-mixed and re-combusted

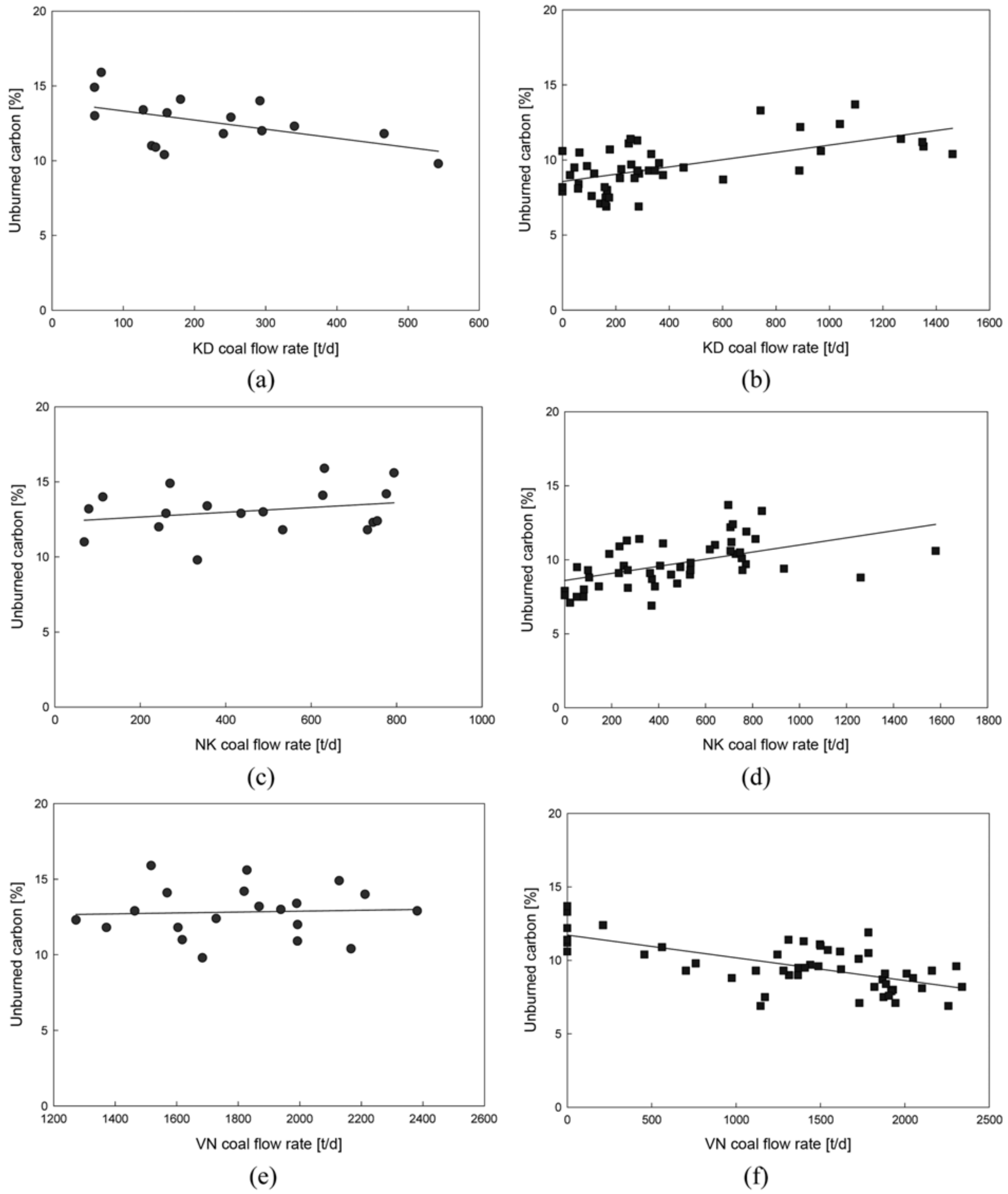

Fig. 3. Effect of coal species (KD, NK and VN coals) and its flow rate on unburned carbon fraction: (a), (c) and (e) #1 unit, (b), (d) and (f) #2 unit.

in the furnace and cyclone exits. Generally, it could be concluded that high content of unburned carbon in flue gas caused the increase of the temperatures of the furnace and cyclones exits. In addition, the increase of consumption of limestone for sulfur capture in the furnace was attributed to the temperature increase of the furnace and cyclone exits due to increase of the unburned carbon fraction as shown in Fig. 6(c) and (d). This may be due to deviation from the optimum desulfurization temperature of limestone, and subsequently due to reduction of reaction surface area of the limestone particles resulting from an increase of sintered surface area at higher operation temperature [10,11].

Fig. 7 shows a change of pressure drop of the upper part of the furnace in #1 and #2 units of the CFB boiler with unburned carbon fraction. The upper part pressure drop in the furnace was known to be dependent on the particle size distribution, gas velocity, solid inventory and solid circulation rate in the furnace [5,12,13]. In the

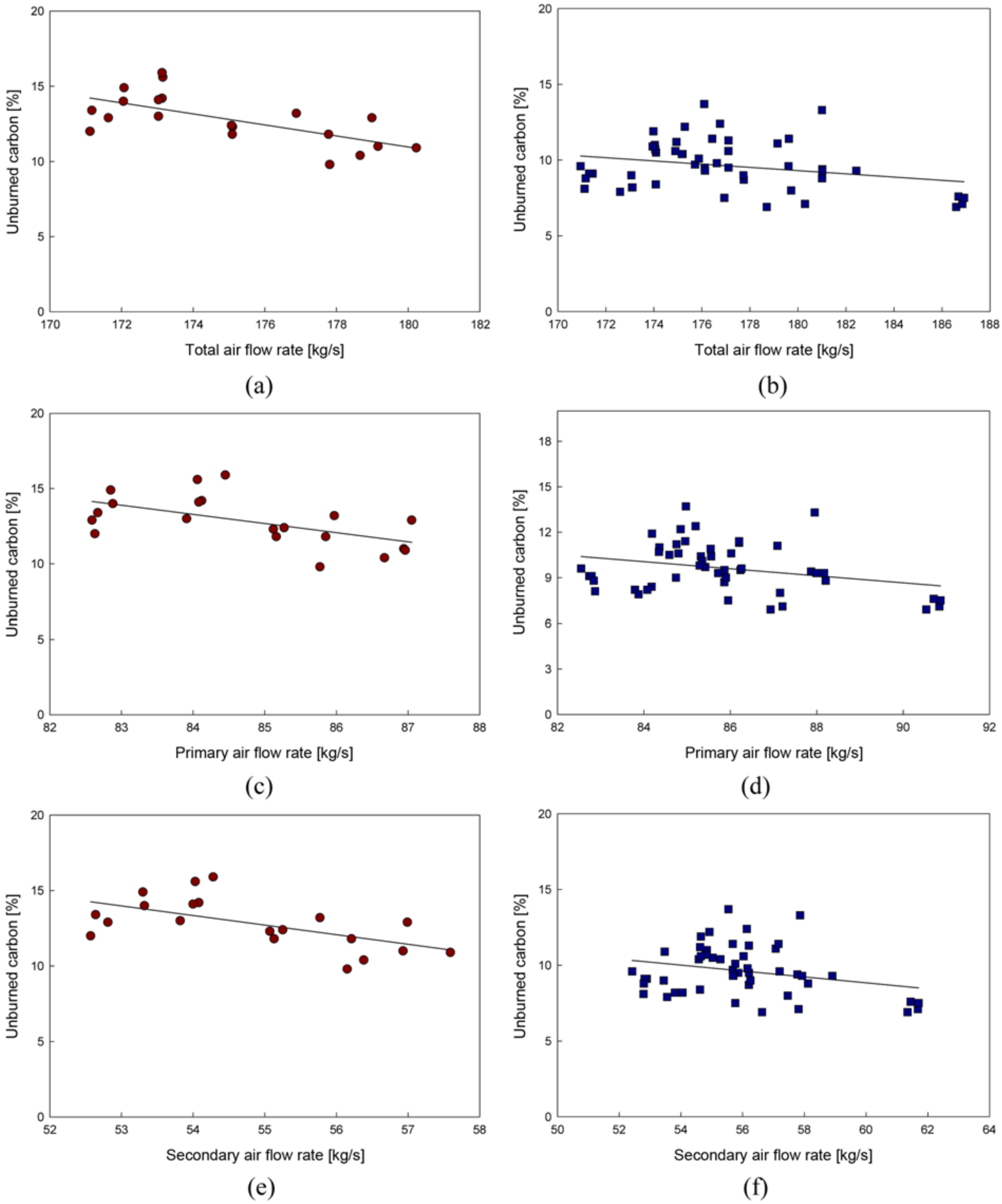

Fig. 4. Effect of air flow rate (total, primary and secondary air) on unburned carbon fraction: (a), (c) and (e) #1 unit, (b), (d) and (f) #2 unit.

case of #1 unit as shown in Fig. 7(a), the unburned carbon fraction decreased with an increase of the upper part pressure drop. The increase of the upper part pressure drop indicates that the unburned carbon fraction was more affected by gas flow rate relevant to excess air ratio rather than by residence time of fine particles relevant to solid move up to the furnace. On the other hand, as shown in Fig. 7(b), the unburned carbon fraction was mainly affected by residence time of fine particles relating to the increase of the upper part pressure in #2 unit of the CFB boiler, because #2 unit was already in the operation condition of enough excess air ratio.

4. Correlation between Unburned Carbon Fraction and Operation Variables

From the results described above, the relations between unburned carbon fraction and operation variables could be observed, in which it was found unburned carbon fraction to be mainly affected by air flow rate and coal species relating to co-combustion ratio in the CFB

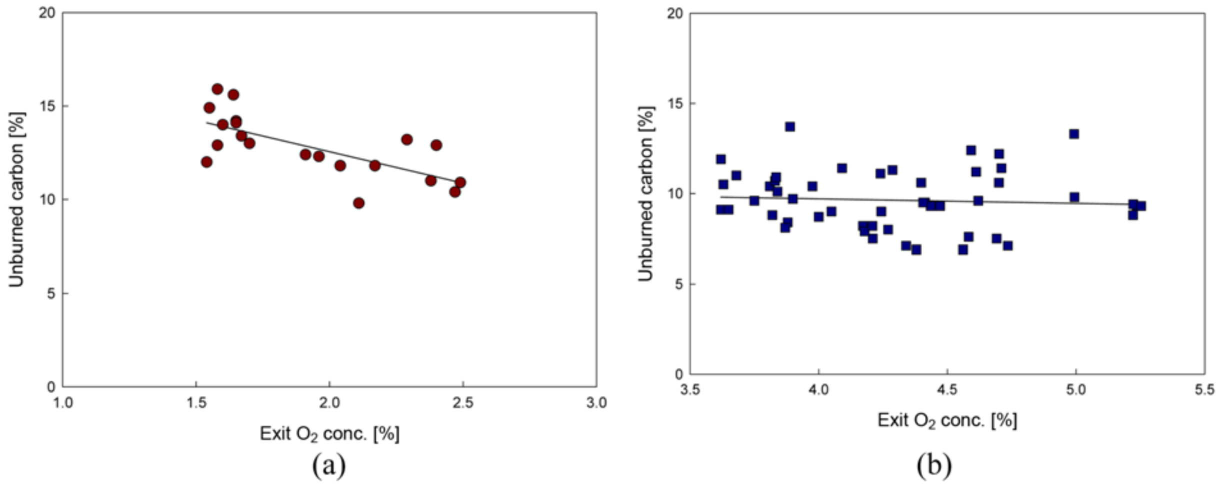

Fig. 5. O_2 concentration at a stack vs. unburned carbon fraction: (a) #1 unit, (b) #2 unit.

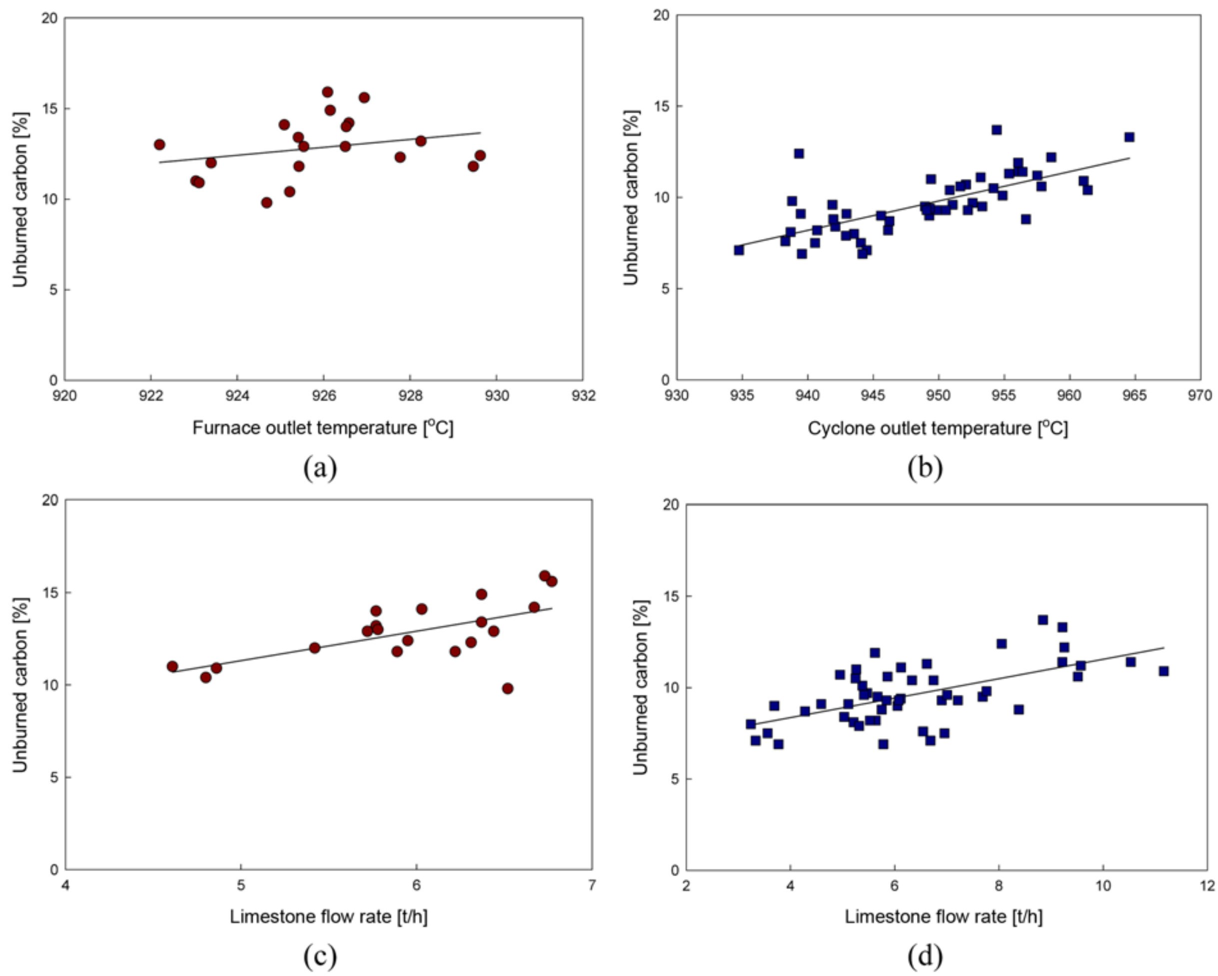

Fig. 6. Furnace and cyclone outlet temperatures and limestone consumption rate with unburned carbon fraction: (a) furnace outlet temperature of #1 unit, (b) cyclone outlet temperature of #2 unit, (c) limestone flow rate of #1 unit, (d) limestone flow rate of #2 unit.

boiler. So the comprehensive correlation for those results in #1 and #2 units of the CFB boiler was deduced and shown in Fig. 8, where the variance in the air flow rate and the unburned carbon fraction against each average value was adopted to correct the fault of the absolute air flow rate. The correlation could be expressed as follows:

$$y=14.87-4.769X_1-0.157\,X_2+0.022\,X_3-0.0006\,X_4-0.0033\,X_5 \quad (1)$$

In correlation Eq. (1), y represents the variance in unburned car-

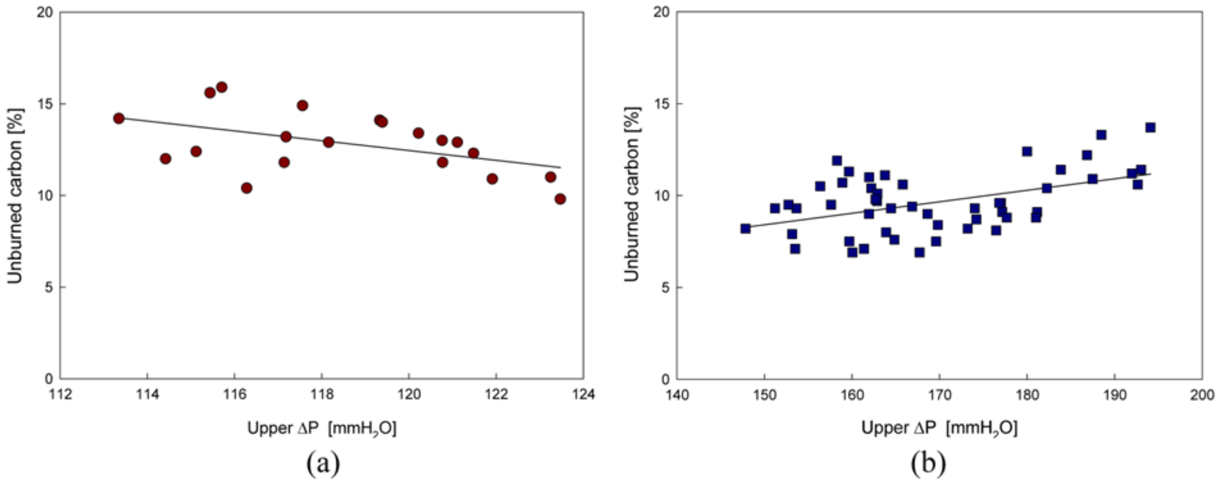

Fig. 7. Pressure drop in the upper part of the furnace with unburned carbon fraction: (a) #1 unit, (b) #2 unit.

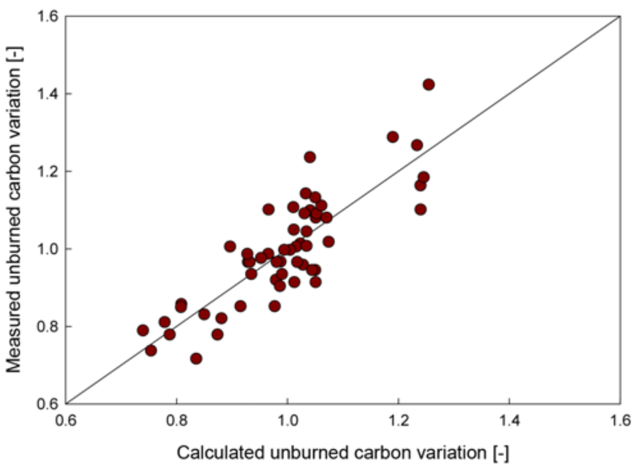

Fig. 8. Comprehensive correlation between unburned carbon fraction in exhaust and operation variables.

bon fraction against its average value, X_1 is the variance in total air flow rate against its average value, X_2 is the ratio of primary air flow rate to sum of primary and secondary air flow rates, X_3 is total coal flow rate, X_4 means the co-combustion ratio of KD coal and X_5 expresses the co-combustion ratio of VN coal respectively. The multiple coefficient of correlation was 0.85 and the correlation could explain well how to reduce unburned carbon fraction in the Tonghae CFB boiler. Ultimately, the directional overall operation such as the increase of total air flow rate and primary air ratio, the increase of co-combustion ratio of KD and VN coals against ND coal should be achieved to reduce unburned carbon fraction in exhaust of the Tonghae CFB boiler.

CONCLUSION

Effects of operation variables such as coal and heat flow rates, air flow rate, co-combustion ratio of each coal, primary and secondary air ratio on unburned carbon fraction in exhaust were observed and analyzed in two units of 200 MWe CFB boiler in the Tonghae thermal power plant.

Unburned carbon fraction in #1 unit of the CFB boiler was mainly affected by air flow rate relevant to excess air ratio and in #2 unit was more affected by coal species and its co-combustion ratio. This seemed to be incurred as the air flow rate of #1 unit was less than that of #2 unit, although the operation conditions of both units were kept at the same values. Also, the co-combustion ratio among KD, ND and VN coals strongly influenced the unburned carbon fraction in #2 unit of the CFB boiler.

From the results, a comprehensive correlation between unburned carbon fraction and operation variables could be deduced with good agreement of 0.85 multiple coefficient of correlation. Ultimately, the directional overall operation such as increase of total air flow rate and primary air ratio, increase of co-combustion ratio of KD and VN coals against ND coal should be achieved to reduce unburned carbon fraction in exhaust of the Tonghae CFB boiler.

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