

# Co-combustion of Bituminous Coal with Anthracite in a Down-firing, 200 MW Boiler

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## Abstract

The combustion tests for Korean anthracite-bituminous coal blend were carried out in the 200 MW utility boiler. The burning characteristics of the blend were studied with a thermogravimetric analyzer (TGA). From the observation of TGA burning profiles, it was found that the presence of bituminous coal in the blend appeared to enhance the reactivity of anthracite in the higher temperature region, indicating certain interactions between the two coals. The plant test showed the boiler operation was reasonably stable with somewhat poor combustion efficiency, and some modification of the combustion environment in the furnace is necessitate for the further stable plant operation.

*Keywords: Coal Combustion, Plant Test, Burning Profiles, Blend, TGA*

## I. INTRODUCTION

Blending of coals of different types in pulverized coal-fired power stations is becoming common practice to save the fuel cost, meet the emission limits (especially SO<sub>2</sub>) and improve the combustion behavior in a commercial boiler. The practical information and techniques for the blended coal combustion in the power station have been reviewed in the literature [1][2]. Both reviews discuss the evaluation and prediction of the behavior of the blends of different rank of coals in many aspects: analytical values of the blend (such as proximate/ultimate analysis, ash fusion temperatures and grind ability etc), combustion behavior (ignition, flame stability, reactivity and burnout), and ash deposition behavior and emission characteristics. These findings in the literature have been focused on the combustion characteristics of the blends consisting of bituminous and sub-bituminous coals (or some lignite) [3]-[10]. However, the information on the combustion behavior of the blends containing anthracite has been rarely found [11][12].

Y power plant in South Korea has a vertically down-fired boiler which was designed to burn Korean anthracite with heavy oil as a supplementary fuel. The main objective of the combustion tests in this study was to investigate the possibility of use of bituminous coal instead of heavy oil, and the attention was focused on the stability and reliability of plant operation, the key issue for the long-term operation and the assessment of technical barriers, etc.

This paper provides a description of burning characteristics of the Korean anthracite-bituminous coal blends in the temperature programmed TGA. The morphology and the ash fusion temperatures of the blend are also studied. The results of combustion tests for the coal blends at Y power station are presented and discussed for the boiler operation, combustion behavior, slagging and emission characteristics.

## II. EXPERIMENTAL

### A. Materials

Korean anthracite and Australian bituminous coal were sampled from the Y power plant in order to analyze coal characteristics and carry out TGA test. Ultimate and proximate analysis, bulk ash composition and heating value for both coals were obtained by standard procedures and their values are given in Table 1. Analysis of heavy oil, burning with Korean anthracite in Y power plant, is also given in the same Table.

### B. Lab. tests

The samples of anthracite and bituminous coal were prepared for morphology analysis, ash fusion temperature (AFT) measurement and TGA test as well as coal characteristic analysis. Each coal was sieved to range between 53 and 75 μm in particle size. The sieved coal samples were used to prepare the binary coal blends for TGA tests and AFT measurement. Chemical morphology analyses of anthracite and bituminous coal were performed for the two coal samples, and the content of anthracite in each blend was varied from 20 to 80 wt.%.

### C. Plant test

#### 1) Description of the boiler

The boiler is a naturally-circulated single-drum type with the balanced draft system, and equipped with a down-firing burner configuration for the efficient burning of anthracite blended with heavy oil. The schematic diagram of the furnace, heat exchangers, burners and air ports in the boiler is presented in Fig. 1, together with a 3-D graphical representation. The firing of anthracite produces long and W-shaped flames in the lower furnace, with the flue gases discharging upward through the center of the furnace. Thirty two coal nozzles are located on the arch of the furnace. The primary air for transporting coal particles to the coal nozzles is around 30 to 35% of the total combustion air, and ejected at the coal nozzles with a velocity of 30 m/s, approximately. The tertiary air, covering about 15 to 25% of the total combustion air, is introduced around the coal

Table 1. Properties of two coals and heavy oil

Fuel properties	Heating value (air-dry, kcal/kg)	Proximate Analysis (air-dry, wt.%)				Ultimate Analysis (dry, wt.%)					
		Moisture	VM <sup>1)</sup>	FC <sup>2)</sup>	Ash	C	H	N	S	O	Ash
Anthracite	4,57	3.59	4.12	57.8	34.49	60.41	0.79	0.42	0.45	2.18	35.75
Bituminous	6,651	2.00	15.60	66.50	15.90	76.15	3.85	0.98	0.09	1.24	17.69
heavy oil	10,329	-	-	-	0.05	85.78	11.33	0.18	2.64	0.06	0.06
Ash Composition	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	SO <sub>3</sub>	others	HGI <sup>3)</sup>
Anthracite	53.98	32.74	4.26	0.82	0.65	0.23	4.32	2.17	0	0.83	89
Bituminous	52.49	23.56	6.89	2.39	1.43	0.79	0.96	0.41	1.25	9.83	74

1) VM : Volatile matter, 2) FC : Fixed Carbon, 3) HGI : Hard Groove Index

Table 2. The fuel feeding condition for the plant test

Item	Baseline	Case 1	Case 2
GEN OUTPUT (kWh)	196.9	195.6	196.7
Anthracite : Bit. coal : Heavy oil (HHV basis)	65.6:0:34.4	55:35:10	50:50:0
Heavy oil flow (ton/hr)	16.8	4.9	0
Anthracite flow (ton/hr)	72.6	60.4	5.2
Bit. coal flow (ton/hr)	0	26.4	38.0

nozzles through adjacent gaps surrounding the coal nozzles. The secondary air ports are located in a row along the front and rear walls of the lower furnace as well as on side walls, as shown in Fig. 1.

## 2) Combustion test

The combustion tests with the blends of anthracite and bituminous coal were recently performed at the 200 MW power plant. Table 2 lists the test conditions. Leveling off the power output to about 196 MW, two cases were tested by changing the feed rates of anthracite, bituminous coal, and heavy oil. Case 1 used the coal blend of 55% anthracite, 35% bituminous coal with the supply of 10% heavy oil, whereas Case 2 was for the coal blend having 50% anthracite and 50% bituminous coal without burning heavy oil. Here, the above percentage is based on the higher heating value of fuel supplied to the boiler. As a reference, the typical case of burning of about 65% anthracite and 34% heavy oil is also given in Table 2 which is designated as the Baseline.

## III. RESULT AND DISCUSSION

### A. Morphology analysis

Fig. 2 shows the SEM micrograph of bituminous coal sample. Mineral in coal is present in three distinct forms. These are: 1) mineral grains that are included in coal particles (included mineral), 2) excluded mineral grains which are separate from the coal particles (excluded mineral), 3) organically-bound mineral. In this study, total 24 points on each coal sample were selected for the chemical composition analysis. Selected 6 points among them are shown in Fig. 2. Tables 3 and 4 list the morphological analysis results for bituminous coal and anthracite, respectively. "All" in Tables 3 and 4 means the averaged value divided by total analysis points. Results are expressed as weight percentage and normalized to 100% on a carbon-free basis.

The morphological analysis results for the bituminous coal sample indicated that minerals in the coal were generally clay

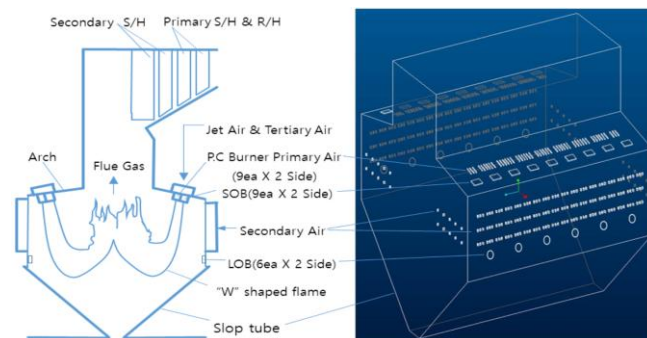


Fig. 1. Schematic and graphical presentation of the W-shaped down-firing boiler

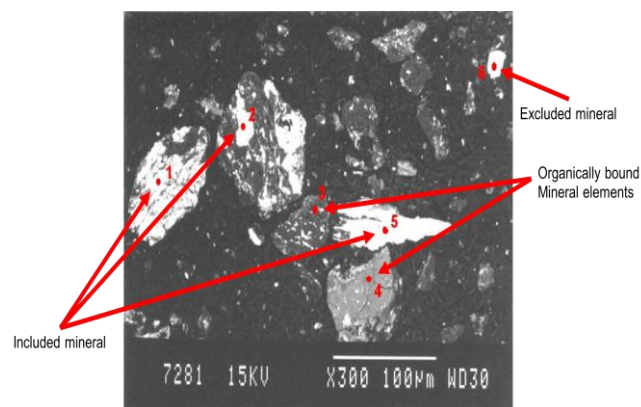


Fig. 2. SEM micrograph of bituminous coal sample

minerals. Other minerals present in the coal included quartz and iron-rich materials. The anthracite coal also contained mainly clay materials. No quartz or iron-rich minerals were observed in this coal sample.

The analysis results of the organically bound mineral in two coal samples are also given in Table 3 and 4, respectively. Al and Si components are much higher in anthracite than bituminous coal while Ca is higher in bituminous coal and Fe in anthracite. This corresponds to the literatures stating that low-rank coal contains relatively large amounts of organically bound elements such as Na, Mg, Ca and K [13][14]. Concerning the present two coals, the portion of organically bound minerals in bituminous coal is higher than those in anthracite, and about 32% of Ca in bituminous coal is highly prominent in the analysis. From the present morphology analyses, the bituminous coal in the blends would contribute to give the generation of fine ash particles and to lower the ash fusion temperature.

## B. Ash fusion temperatures

of bituminous coal is almost finished, whereas anthracite starts the main reaction at this temperature. The DTG curve for

Table 3. Morphological analysis results for bituminous coal

Description	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Ba	O
All	0.61	0.83	12.26	28.69	0.87	1.73	0.15	4.23	8.08	0.96	9.07	1.68	30.85
Included minerals	0.83	0.46	15.68	33.11	1.50	0.00	0.10	3.14	1.13	1.54	5.93	2.70	33.87
Excluded Minerals	0.21	1.22	9.09	19.70	0.00	0.80	0.06	1.38	3.86	0.26	25.72	0.52	37.19
Organically bound mineral	0.36	1.49	5.84	25.29	0.00	7.52	0.38	10.12	31.77	0.00	1.20	0.00	16.03

Table 4. Morphological analysis results for anthracite coal

Description	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Fe	Ba	O
All	0.16	0.38	17.25	26.10	0.00	0.00	0.12	4.39	1.72	0.17	6.45	2.85	40.42
Minerals in coal	0.13	0.49	17.41	21.88	0.00	0.00	0.11	3.94	0.07	0.32	6.55	0.51	48.59
Minerals-excluded	0.30	0.38	17.70	23.87	0.00	0.00	0.19	4.30	0.45	0.00	4.29	0.17	48.34
Organically bound mineral	0.00	0.00	15.93	43.71	0.00	0.00	0.00	6.03	9.29	0.00	9.91	15.13	0.00

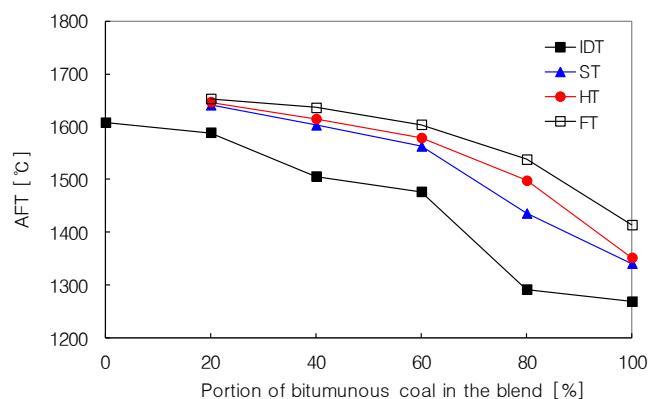


Fig. 3. AFT measurement for the coal samples

Fig. 3 shows the ash fusion temperatures for the present coal blends. The ash fusion temperatures are plotted against the weight percentage of bituminous coal in the blend. The softening, hemispherical and fluid temperatures of anthracite could not be measured, so their values would be over 1,650°C. As seen in Fig. 3, the ash fusion temperatures decrease with the increase of bituminous coal in the blend. However, AFT is not proportional to the portion of bituminous coal in the blend, and the proportionality is poor for all temperatures (IDT, ST, HT and FT). Clearly, ash fusion temperatures are not additive. Lloyd et al(1993) reported that AFT of blends increases with increasing amounts of  $Al_2O_3$ ,  $CaO$ ,  $K_2O$ ,  $Na_2O$  and  $TiO_2$ , and consistently decreases with increasing amount of  $Mg$ ,  $SO_3$  and  $SiO_2$  [15]. For the present anthracite and bituminous coal, the AFT of blends follows the findings of Lloyd et al. (1993) [15]. It is clearly noticed that, with the increase of bituminous coal in the blend, the amounts of  $Al_2O_3$ ,  $K_2O$  and  $TiO_2$  decrease and  $MgO$ ,  $SO_3$  and  $SiO_2$ . Therefore, the AFT decreases with increasing the proportion of bituminous coal in the blend.

## C. Burning Profiles of the coal blends in TGA

The thermo-gravimetric (TG) and the differential thermo-gravimetric (DTG) curves of anthracite, bituminous coal and their blends are shown in Figs. 4 and 5, respectively. For bituminous coal, the DTG curve shows two distinct peaks after the moisture elimination below 200°C. The first peak, which occurs around 460°C, could be attributed to the evolution of volatiles and the second peak occurring around 550°C could be a result of the oxidation of carbon. Around 620°C, the reaction

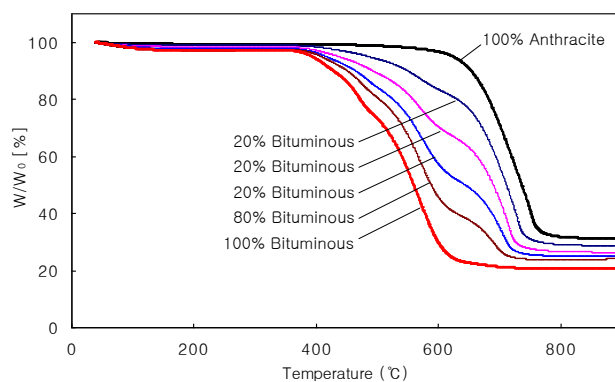


Fig. 4. TG curves of the coal samples

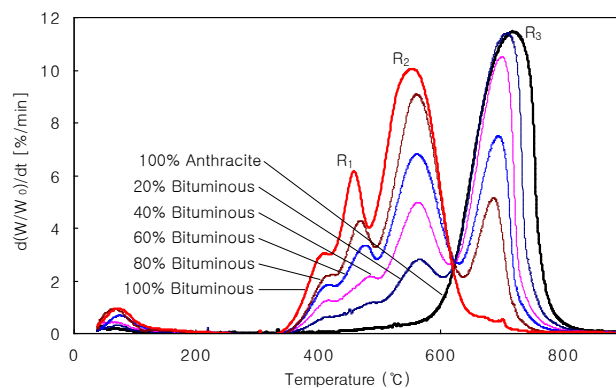


Fig. 5. DTG curves of the coal samples

anthracite gives single peak at high temperature of around 720°C, and the reaction is completed around 800°C.

As seen in Fig. 5, the burning profiles of anthracite-bituminous coal blends represent the three distinct peaks. It is observed that the first and second peaks are from the reaction of bituminous coal, and the third one from that of anthracite. As the proportion of bituminous coal in the blends increases, the first and second peaks more clearly appear in the low temperature region. The third peak in the higher temperature region becomes lower with the increase of bituminous coal in the blend.

In order to investigate the interactions between the present two coals, it is convenient to compare the theoretical DTG curves with the experimental DTG curves for the blends [16]. The theoretical curves are the summation of the DTG curves of the component coals, and expressed as:

$$(dm/dt)_{sum} = x_a(dm/dt)_a + x_b(dm/dt)_b \quad (1)$$

where  $x_a$  and  $x_b$  are the mass fractions of anthracite and bituminous coal in the blends, and  $(dm/dt)_a$ ,  $(dm/dt)_b$  the rates of weight loss found from the individual TGA test, respectively.

Table 5. Plant data for the unburned carbon in ash and CO concentration

Item	Baseline	Case 1	Case 2
CO(ppm)	1000	528	269
Carbon in fly ash (%)	11.61	9.6	11.2
Carbon in bottom ash (%)	10.24	13.6	17.3

Table 6. Major boiler operation data

Item	Baseline	Case 1	Case 2
MS PR.(kg/cm <sup>2</sup> )	169.8	169.3	169.0
MS TEMP.(°C)	540.4	540.0	541.5
RS PR.(kg/cm <sup>2</sup> )	26.7	28.3	28.5
RS TEMP.(°C)	540.5	540.3	541.4
S/H SPRAY FLOW(T/H)	91.1	37.6	62.3
ECO. OUT Gas O <sub>2</sub> (%)	1.36	2.16	1.71
TOTAL AIR FLOW (%)	77	71	73
Furnace Gas Temp.(°C)	N.A	844	970
A/H IN AIR TEMP.(°C)	46	30	22
A/H IN GAS TEMP.(°C)	433	408	441
A/H OUT GAS TEMP.(°C)	175	158	176

Table 7. Flue gas emission data

Item	Baseline	Case 1	Case 2
NO <sub>x</sub> (ppm)	220	227	296
SO <sub>x</sub> (ppm)	90	47	40
DUST (mg/s·m <sup>3</sup> )	29	28	32

The theoretical and experimental DTG curves for 20% bituminous coal blend are given in Fig. 6. The individual DTG curves of anthracite and bituminous coal are also presented in the figures. It is observed from the four curves that the discrepancy between theoretical DTG curves to the experimental ones is significant, especially in the high temperature zone than in the low one. Above 620°C which is responsible for the burning of anthracite, the experimental burning profiles precede the theoretical ones. The experimental burning profiles below 620°C for which bituminous coal is responsible are retarded when comparing them with the theoretical ones. The discrepancy between the theoretical and experimental burning profiles is clearly prominent in the high temperature region at which anthracite mainly reacts, rather than in the low temperature zone at which bituminous coal mainly reacts. Therefore, some interactions between two coals of different rank seem to be occurred in the region of the less reactive coal combustion.

#### D. Combustion tests at 200 MW power plant

##### 1) Grinding behavior

Y power station has four units of double-ended ball-tube mill. The blended anthracite and bituminous coal was pulverized in the tube mill and re-sized in the classifier, and then transported directly to the furnace without pulverized coal storage bunkers. The classifier outlet temperature was

maintained to be under 85°C by regulating the air temperature from the forced draft fan. The fineness of pulverized coal blends was maintained to be in the usual range of 85% less than 200 meshes. The power consumption of the mill was at the normal level during the tests.

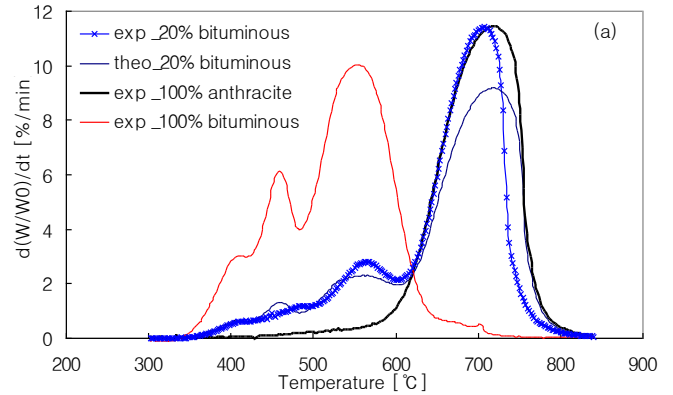


Fig. 6. The theoretical and experimental DTG curves

##### 2) Combustion behavior

During the tests, the fluctuation of the blended coal flame was sometimes observed and the CO concentration measured at the outlet of economizer gave the fluctuated values, occasionally. Although irregular, unsteady combustion was occasionally observed in the furnace, the overall flame stability of anthracite-bituminous coal blends was not behind to those in burning of anthracite with heavy oil. However, the position of W-shaped flame for Case 2 was observed to be lifted upward, compared with that for Case 1. The faster burning of bituminous coal in the blend might be responsible for this lifted flame. The CO concentrations were maintained somewhat high level throughout all tests, as given in Table 5, but to be lower level than that for Baseline.

##### 3) Slagging

During the combustion tests, the slagging behavior in the furnace was observed visually and recorded by CCD camera. The ash deposition on the side and arch wall was prominent during the tests. The thick deposition ranging from 10 to 30 cm was occasionally found near the coal burner on the arch wall. From the AFT measurements and morphology analysis, the severer slagging propensity was expected in Case 2 than Case 1. The respective furnace exit gas temperatures (FEGTs) for Case 1 and 2 are 844°C and 970°C (Table 6), which also implied that the slagging tendency in the furnace might be severer in Case 2 than in Case 1. During the tests, it was identified that the extent of slagging in the furnace is higher in Case 2 than Case 1.

##### 4) Boiler operation

The major variables of the boiler operation for Cases 1 and 2 are summarized in Table 6, together with those for the Baseline. It was observed that the pressure and temperature of main and reheated steam for Cases 1 and 2 are quite close to those for the Baseline. The general process values for Cases 1 and 2 were maintained at the normal level, and the compatibly stable boiler operation was achieved during the tests. The FEGT for Cases 1 and 2, measured just in front of final superheater (See Fig. 1), are 844°C and 970°C, respectively. The higher

temperature in Case 2 than Case 1 might attribute to the fact that the lifted flame and relatively poor combustion efficiency occurs in Case 2. Furthermore, the poorer heat adsorption in the furnace is expected in Case 2 than Case 1 from the viewpoint of slagging tendency as discussed above. The higher FEGT in Case 2 than in Case 1 could result in the increased superheated spray water flow and the higher gas temperature at the air heater. Therefore, the air heater inlet air temperature had to be reduced further (from 30°C to 22°C ) in order to compensate for the increased air heater inlet gas temperature (from 408°C to 441°C). Overall, it has been experienced during the tests that the more attention has to be paid for the stable boiler operation as well as the enhancing combustion efficiency.

#### 5) Flue gas emission

Table 7 shows the average concentrations of SO<sub>2</sub>, NO<sub>x</sub> and dust at the boiler outlet. The dust concentrations for the three cases were not different much. The amounts of ash fed into the furnace were very similar to each other, so that the concentrations at boiler outlet were presented to be the same level for the three cases. The SO<sub>2</sub> concentration had a similar level for Cases 1 and 2. The NO<sub>x</sub> emission was significantly increased to 296 ppm in Case 2, but it would be reduced with a proper manipulation of the firing condition in the furnace.

### IV. CONCLUSION

The morphological analyses for anthracite and bituminous coal sample indicated that minerals in the coal were generally clay materials. It was found that the proportion of organically bound minerals in bituminous coal is higher than that in anthracite, and Ca in bituminous coal is highly prominent (32%) in the analysis. From the standard AFT test, the ash fusion temperatures of the blends obtained showed a non-linear behavior between two coals, which implied that they are clearly not additive.

The burning profiles of anthracite-bituminous coal blends exhibited distinct peaks depending on the blending ratio between the two coals. It could be concluded that the burning of anthracite is affected, in positive way, by the preceding reaction of bituminous coal, enhancing the char reactivity of anthracite.

During the plant tests, the less stable combustion and lifted W-shape flame were observed in the furnace as the proportion of bituminous coal was increased in the blend. The extent of slagging was severer in Case 2 than Case 1. The general process values were maintained at the normal level and the compatibly stable boiler operation was achieved. However, the higher FEGT in Case 2 than Case 1 was thought to be from the result of the lifted flame and relatively poor combustion efficiency, which could cause somewhat abnormal boiler operation.

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