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Co-combustion of Korean anthracite with bituminous coal in two circulating fluidized bed combustors

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Abstract−The co-combustion characteristics for Korean anthracites and bituminous coals were determined in a lab-scale CFB reactor and the commercial scale Tonghae CFB Power Plant. In the lab-scale CFB combustion tests, the effluent rate of the emission gases, which can indicate the reactivity of the combustion, did not change appreciably when each coal burned. As the bituminous coal was added, however, the effluent rate of the emissions increased. The amount of the unburned carbon in ash decreased with increasing the ratio of the bituminous coal during the co-combustion. When the co-combustion was tested in the Tonghae CFB power plant, the temperatures at the upper part of the combustor and the cyclones, which were somewhat higher than designed and expected, could be reduced as the bituminous coal ratio increased. Consequently, more stable operation of the CFB boiler was achieved. The efficiency of the CFB boiler also increased due to increasing the reactivity of the combustion.

Key words: CFB, Co-combustion, Korean Anthracite, Tonghae Boiler

INTRODUCTION

Recently, interest in the effective utilization of fule has increased since most energy consumption in Korea is dependent on imported energy resources. Moreover, due to the increase in oil prices, the energy utilization technology is more important [1]. One of the successful technologies for energy utilization in Korea is a circulating fluidized bed combustion technology because of its capability of burning a variety of fuels, especially poor quality Korean anthracite [2,3].

Korea Electric Power Corporation (KEPCO) constructed the 2× 200 MWe Tonghae CFB boilers in 1998 and 1999, respectively. The CFB boiler uses Korean anthracite as a fuel without assistant fuel such as heavy oil, although some facilities firing the anthracite use assistant oil due to the low combustion reactivity of the coal [4]. However, the anthracite had the combustion efficiency to be lower and the operating conditions of the CFB boiler to be unstable. Also, the utilization of the CFB boiler has been gradually restricted because of the insufficient production and supply of the anthracite and its high fuel cost [2,4].

Some researchers have been studying co-combustion of coal with biomass, sewage sludge, and wastes in a CFB boiler and are verifying in medium and small scale CFB boiler [5-8]. But most studies are focused on the environmental effect for some addition of low quality fuel into good combustible bituminous coal.

The main purpose of this study was to determine the co-combustion behavior based on the poor quality anthracite with an addition of rich volatile bituminous coal and to check the improvement of the combustibility of the anthracite. It will provide a useful reference for applying co-combustion of the anthracite and bituminous coal to a commercial CFB boiler.

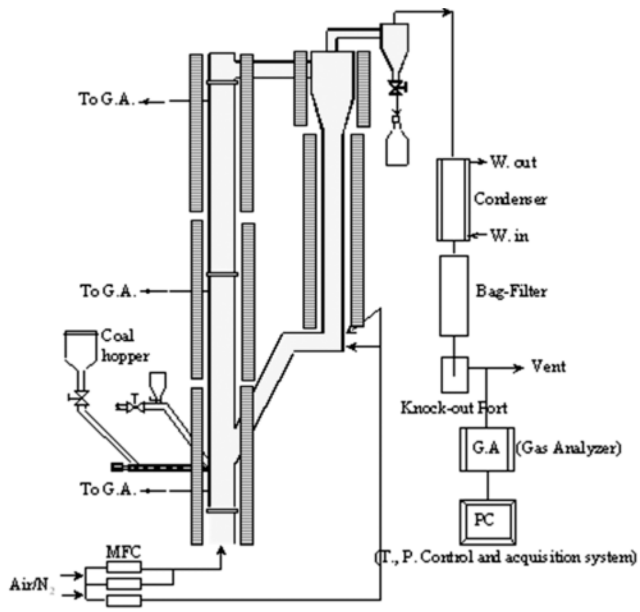

Fig. 1. Schematic diagram of experimental apparatus.

EXPERIMENTAL

The lab-scale CFB reactor used in this study is shown in Fig. 1. It consists of a stainless steel main reactor, a gas (N_2 and air) supply system, a coal feeding system and a flue gas treatment and analysis system. The main reactor is composed of a riser (ID=35 mm, H= 2.3 m), a downcomer (ID=25 mm), two cyclones and an L-valve. The main reactor is electrically heated to a desired temperature by five external furnaces surrounding the main reactor. To measure the temperature and pressure of the reactor, 13 thermocouples and 10 pressure transmitters are located along the reactor. Coal particles

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Table 1. Analyses of Korean anthracite and bituminous coal used for co-combustion

Coal	Do gae	Dong won	Sam choek	Gyung dong	Jang sung	Han bo	Tae baek	MIM	Roto south	Blairathol	Anthracite*	Bituminous coal**
Proximate analysis (wt%)												
Moisture	3.26	3.07	3.60	3.76	2.82	4.46	4.15	1.52	7.97	3.19	3.84	2.37
VM	3.90	4.33	3.89	3.92	5.00	4.09	3.68	24.27	43.02	26.05	7.50	30.17
FC	60.86	51.00	58.44	65.32	47.02	60.40	61.58	58.28	42.17	62.61	53.31	52.06
Ash	31.98	41.60	34.07	27.00	45.16	31.05	30.59	15.73	6.84	8.15	35.35	15.40
Ultimate analysis (wt%)												
C	63.21	52.58	60.76	68.79	49.41	63.74	64.38	72.73	76.00	65.73	59.77	71.33
H	0.77	0.77	0.82	0.79	0.80	0.79	0.80	4.23	4.10	4.48	0.98	4.54
O	2.16	3.01	2.41	0.83	2.48	2.10	2.16	5.38	9.60	21.45	1.47	5.94
N	0.39	0.36	0.43	0.43	0.40	0.46	0.50	1.46	1.69	0.88	0.35	1.57
S	0.41	0.36	0.24	1.10	0.44	0.41	0.22	0.23	0.19	0.04	0.49	0.65
Ash	33.06	42.96	35.34	28.06	46.47	32.50	31.92	15.97	8.42	7.42	36.94	15.97
Heating value***											4,812	6,844

*Tested in the Tonghae CFB boiler, ** tested in the Tonghae CFB boiler, *** dry basis.

are fed through a batch feeder using pressurized N_2 for injection of the particles. Silica sand with a mean diameter of 90 mm is used as bed material. A PC connected with the CFB reactor is used for controlling the operation condition and storing all operation and measurement data.

The Tonghae CFB boiler, in which commercial scale co-combustion tests were carried out, has been described in many previous studies [4,9]. The boiler consists of a furnace (19 m-W×8 m-L×32 m-H), three cyclones and loopseals, three fluidized bed heat exchangers and a fluidized bed ash cooler. The boiler capacity is 200 MWe and has been commercially operated since 1998.

The analyses of the coal used in this study are shown in Table 1. Korean anthracites (Dogae, Dongwon, Samchoek, Gyungdong, Jangsung, Hanbo, Taebaek) have comparatively rich ash and low volatile content, whereas bituminous coals (MIM, RotoSouth, Blairathol) have comparatively rich volatile and low ash content. The coals used for co-combustion test in the Tonghae CFB boiler are also shown in Table 1.

Co-combustion tests for the anthracite and the bituminous coal in the lab-scale CFB reactor are carried out by the following steps. When steady-state is achieved after a certain time for heat-up, a given amount of fluidizing air is introduced to the riser and the L-valve. At this time, air is injected into the riser with a suitable flow rate, maintainiing a desired temperature by an air-preheater. When the test condition is completed, the coal particles with a uniform size are introduced through the batch feeder all at once and then emission gases are analyzed by the IMR-2000 and CO_2 analyzer. After a certain time for a co-combustion test, all particles in the CFB reactor are quenched and removed to analyze the unburned carbon. In addition to switching off the air supply and heating to the CFB reactor, introducing cold N_2 to the reactor performs the quenching process. After the unburned carbon is analyzed, the particles are sieved to separate the silica sand, which can be separated easily from the coal particles due to its smaller size and reused as bed material. The mass of coal particles smaller than 100 mm can be calculated by the previously proposed mass balance [9].

Table 2. Operating conditions for co-combustion test

Variables of lab-scale CFB reactor	Operating conditions
Fluidizing gas	Air (quenching gas: N_2)
Operating pressure	Atmosphere
Bed temperature	820-880 °C-Riser, 750-800 °C-Downcomer
Superficial gas velocity	1.2 m/s
Bed material	Silica sand (d_p=90 μm)
Mass of coal fed	2-6 g
Size of coal	2-4 mm
Bituminous coal ratio	0-50%
Variables of the Tonghae CFB boiler	**Operating conditions**
Power Generation	150 MWe
Total air flow	128-131 kg/s
Total coal flow	69.5-75.2 ton/h
Bituminous coal ratio	0, 10, 20, 30%

On the other hand, co-combustion tests in the commercial scale Tonghae CFB boiler were carried out at a constant power generation in which only the coal flow rate and the ratio of bituminous coal to anthracite were varied. The experimental conditions are shown in Table 2.

RESULTS AND DISCUSSIONS

1. Test in the Lab-scale CFB Reactor

Fig. 2 shows the variation of emission gas concentrations during the combustion of the anthracite (Dongwon). As shown in Fig. 2, the concentrations of the emission gas increase drastically at the early stage of the combustion with increasing the amount of anthracite. In the case of the batch feeding combustion, most reactions including devolatilization occur at the early stage, and the remaining char combustion reaction occurs continuously on the latter half. After an explosive reaction at the beginning of the combustion, the

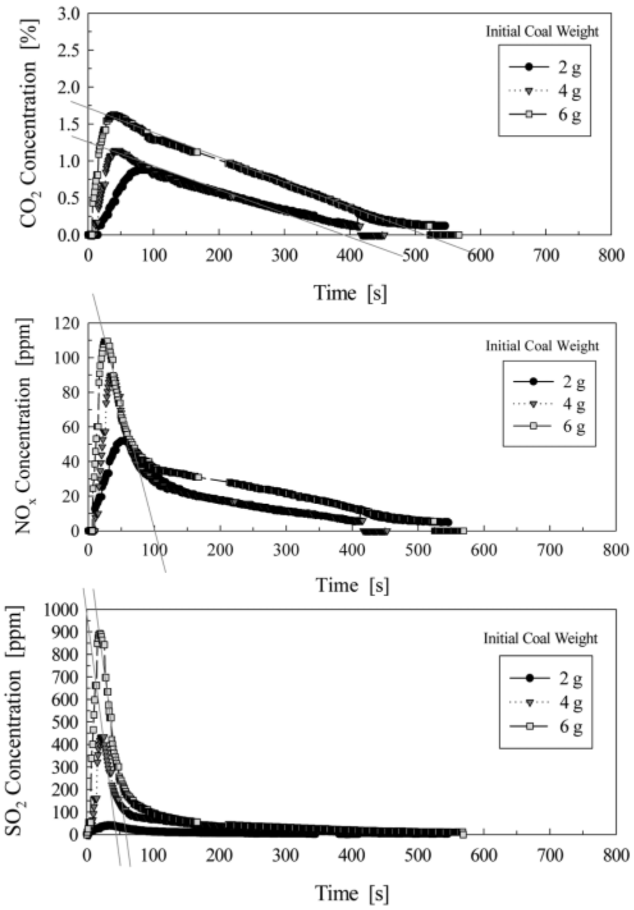

Fig. 2. Gas emission during combustion of the anthracite (Dongwon).

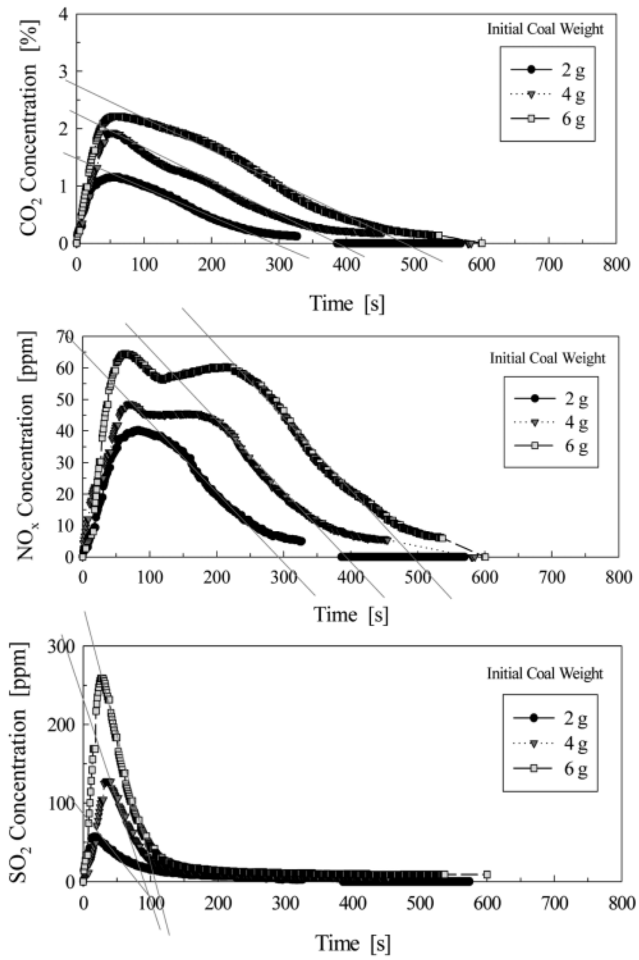

Fig. 3. Gas emission during combustion of the bituminous coal (Rotosouth).

slopes of gas emissions are almost uniform and the same. The slopes are calculated by 1st regression from the maximum point of devolatilization to the point which is kept on within 5% variation of slopes of emission gases. As shown in Fig. 2, the change of the slopes of emission gases is not appreciable, so the variation of the combustion reactivity is found to be kept with increasing the amount of the coal fed.

The characteristics of gas emissions during the combustion of the bituminous coal (Rotosouth) are also shown in Fig. 3. The trend of gas emissions of the bituminous coal is not different from that of the anthracite. The slopes of the gas emissions during the combustion are not dependent on the amount of the coal fed. This result means that the rates of gas emissions are uniform due to the same combustion reactivity, although the amount of gas emissions increases with the amount of the coal fed. In the case of SO_2 emissions, the interrelationship with the combustion reactivity is shown to be somewhat low, which may be affected by the irregular dispersion of S in the volatiles and the char of the coal.

The gas emissions for the co-combustion of the anthracite and the bituminous coal are very different from those of the combustion of the anthracite or the bituminous coal. As the ratio of the bituminous coal increases, the slope of the gas emissions increases. This means that the rate of the gas emissions during the co-combustion is affected by the reactivity of the bituminous coal. The slope of gas emission rate with the ratio of the bituminous coal during the co-combustion can be calculated by the same method shown in Fig. 2 and Fig. 3, and is expressed in Fig. 4. The slopes of gas emission rates increase with increasing the ratio of anthracite to bituminous coal. Also, some values for CO_2 and SO_2 emissions are larger than expected values expressed by a straight line from 0 to 100% ratio of the bituminous coal. This means that the co-combustion, which leads to the improvement of the combustion reactivity, may be caused by more formation of volatile component, such as H_2, O_2 and hydrocarbon compound.

Fig. 5 shows the unburned carbon fraction after co-combustion. It can be observed that the UCF decreases as the ratio of the bituminous coal increases. It comes from the increase of the amount of the bituminous coal which has good combustible property and from the improvement of the combustion reactivity of the anthracite. However, the decreasing trend of UCF changes at about 50% ratio of the bituminous coal. This may be from the decrease of the ash content with increasing the ratio of the bituminous coal though the practical amount of the unburned carbon decreases.

Therefore, it can be determined that the co-combustion of the anthracite with the bituminous coal improves the combustion reactivity and consequently reduces the unburned carbon in the ash.

2. Test in the Commercial Scale Tonghae CFB Boiler

A commercial scale co-combustion test in the Tonghae CFB boiler

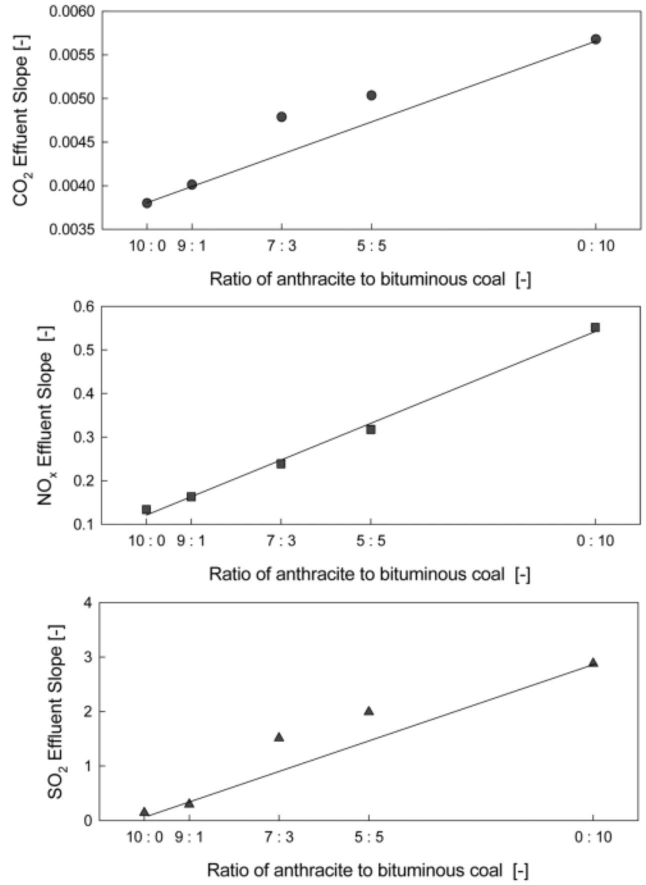

Fig. 4. Slope of the gas emission rate during co-combustion.

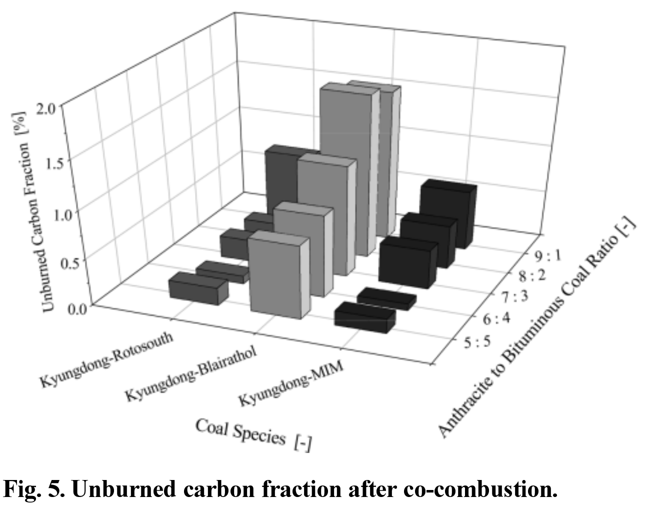

Fig. 5. Unburned carbon fraction after co-combustion.

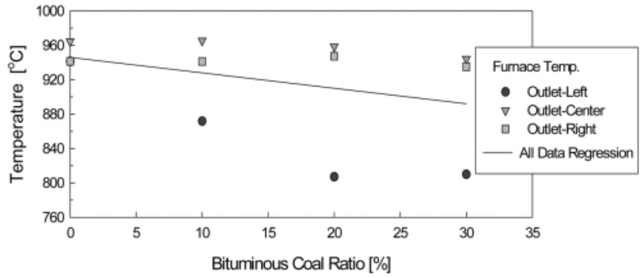

Fig. 6. Effect of bituminous coal ratio on the temperature of the furnace outlet.

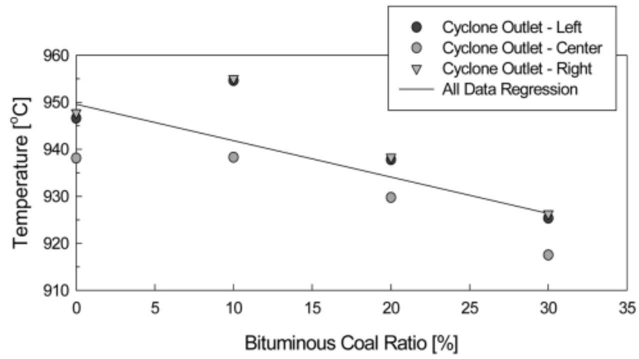

Fig. 7. Effect of bituminous coal ratio on the temperature of the cyclone outlet.

was carried out at constant power generation. The change of the temperature distribution makes it possible to analyze the status of the co-combustion of the anthracite and the bituminous coal shown in Table 1. The temperature measurement was done at 3 different furnace outlets at a height of 28 m above the distributor and 3 different cyclone outlets (two sides and a center of cyclone).

Fig. 6 shows the temperature of the furnace outlet with the ratio of the bituminous coal during co-combustion and the all data used in the figure were obtained by averaging data for 12 hours for each co-combustion case. As shown in the Fig. 6, it can be observed that outlet part temperature of the combustor becomes lower with increasing the ratio of the bituminous coal. This trend can be also seen from the temperatures of the cyclones shown in Fig. 7.

The temperature reduction of the furnace and cyclones outlets can be caused by the rapid combustion of bituminous coal in the lower part of the furnace. Compared with anthracite, bituminous coal used for the co-combustion has much volatile content and rapid combustion reactivity. So, most of the combustion occurs at the lower part of the combustor. The temperature reduction of the furnace and cyclone outlets of the Tonghae CFB boiler is very important. First, the reliability of the boiler operation increases. The operation temperature of the Tonghae CFB boiler has been limited by the temperatures of the furnace and cyclone outlets, which are usually the highest due to the post-combustion of the anthracite [2]. Therefore, this temperature reduction makes it possible to extend the capability of controlling the operation of the CFB boiler. The second is that room for increasing the combustion efficiency can be obtained. The easy way to improve the combustion efficiency is to raise the combustion reactivity through the temperature elevation of the combustor. However, in the Tonghae CFB boiler, this is very difficult, because it can lead to a rise in temperatures of the furnace and cyclones outlets. That is, the reduction of the temperatures of these plants makes it possible to improve the combustion efficiency. The third is that the efficiency of desulfurization can be increased. Generally, limestone which is used for a desulfurizing agent, has the best reactivity about 850 °C, but over 900 °C the efficiency of desulfurization decreases due to the deactivation of limestone [10]. So, the reduction of the highest temperature of the CFB boiler can

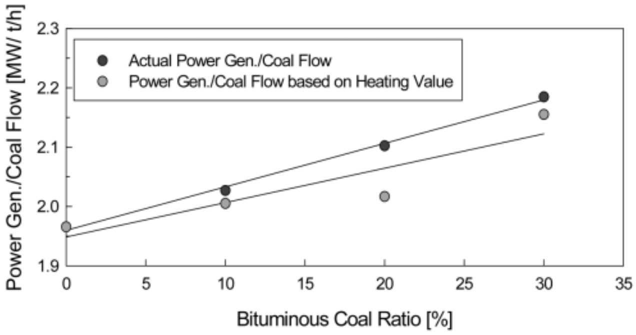

Fig. 8. Power generation/coal flow with bituminous coal ratio.

prevent limestone from deactivating and can improve the efficiency of the desulfurization reaction.

Fig. 8 shows a comparison of the power generation per coal flow rate between the actual obtained data and the expected values based on heating value of the coal fed. The power generation per coal flow rate based on heating value of the coal fed is smaller than that of actual power generation per coal flow rate with the bituminous coal ratio during co-combustion. It means that the actual power generation is bigger than that of theoretical power generation. This may be from improvement of the combustion reactivity of the anthracite through the co-combustion with the bituminous coal, as observed in test results from the lab-scale CFB reactor.

CONCLUSIONS

The co-combustion characteristics of Korean anthracites and the bituminous coals were determined in the lab-scale CFB reactor and the commercial scale Tonghae CFB Power Plant.

In the co-combustion test using the lab-scale CFB reactor, the emission rate of the gases did not change appreciably when each coal burned, and the rate was almost uniform with varying the amount of coal fed. However, as the ratio of the bituminous coal increased, the effluent rate of the gas emissions increased. The unburned carbon in ash decreased with increasing the ratio of the bituminous coal during co-combustion.

In the commercial scale Tonghae CFB boiler, the temperature of the furnace and cyclones outlets decreased with increasing the ratio of the bituminous coal. Also, the power generation per coal flow rate based on heating value of the coal fed is smaller than that of actual power generation per coal flow rate with the bituminous coal ratio during co-combustion. Consequently, more stable operation of the CFB boiler was achieved and the boiler efficiency also increased due to the increase of the reactivity of the combustion.

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