Evaluation of Combustion Characteristics for Blended Coal

Sung- Chul Kim, Jong- Jin Kim, Hyun- Dong Lee, Tai- Hyeung Kim, Young-Jin Shin, Seung- Han Yang

Power Generation Laboratory, Korea Electric Power Research Institute
103-16 Munji-dong, Yusung-gu, Taejon,305-380, KOREA

ABSTRACT

KEPRI has a pilot-scale combustion test facility, which can offer versatile tools to study coal-related impacts on utility boiler operations. The facility, a scale-down model of an existing boiler, consists of all the necessary components for the boiler except steam generation component. Various test probes are installed to monitor pulverizer performance, combustion stability, slagging, fouling, heat transfer, and pollutant emission, *etc.* Also, it incorporates the advanced boiler technologies such as flue gas recirculation, direct sorbent injection for desulfurization, electrostatic precipitator, and wet scrubber. Flow fields in the furnace can be controlled by varying the swirl number and by changing the burner configurations from single-wall to opposed-wall or corner firing mode. In this paper, combustion test results of blends of sub-bituminous and bituminous coals are presented. In this test, combustion characteristics in terms of unburned carbon, N0x, S0x, fouling, and temperature profile as functions of coal fineness and excess air ratio were evaluated.

1. INTRODUCTION

Coal burning power units comprises 27.0 % of the total installed capacity of 43,910 *MW* in KEPCO. As of 1998, coal consumption in coal fired power units amounts to 28.2 million tons. It is anticipated that the share of the units will gradually increase up to 30 % and coal consumption will be doubled by the year 2005. Coal is relatively inexpensive and thus, effective for utility power generation. However, the coal-fired power plants generate a considerable amount of pollutants and has been a target of environmental regulations [1]. Therefore, coal selection should be based not only on the cost of the coal per unit combustion energy but also the cost caused by any adverse impacts on environmental problems. Often coal blending is practiced to meet the environmental regulations. However, coal blending can affect the boiler performance, and therefore, blending is conducted in such a way that properties of blended coals are close to those of the design coal for the power plant in consideration It is thus required in advance to evaluate coals to see if the coals satisfy the coal specifications, to find optimum combustion conditions for power plants to be used, and to meet stringent environmental regulations. Combustion characteristics of the coals have been determined by utilizing several indirect methods including proximate and ultimate analyses, thermogravimetric analysis, and drop tube furnace tests. However, it is believed that direct combustion test with pilot-scale furnace would be the best way to simulate combustion phenomena of real utility boiler [2,3]. In the present paper, test results on combustion characteristics of blends of sub-bituminous and bituminous coals are discussed, using the pilot-scale combustion test furnace at KEPRI.

COMBUSTION TEST FURNACE

Fig. 1 shows the combustion test furnace, a scale-down model of the existing utility boilers in Korea. There are slag panels instead of water wall tube to extract combustion heat at the radiant section. The main purpose to construct this facility is to evaluate the coal combustion characteristics on utility boiler. The impacts being investigated with operation

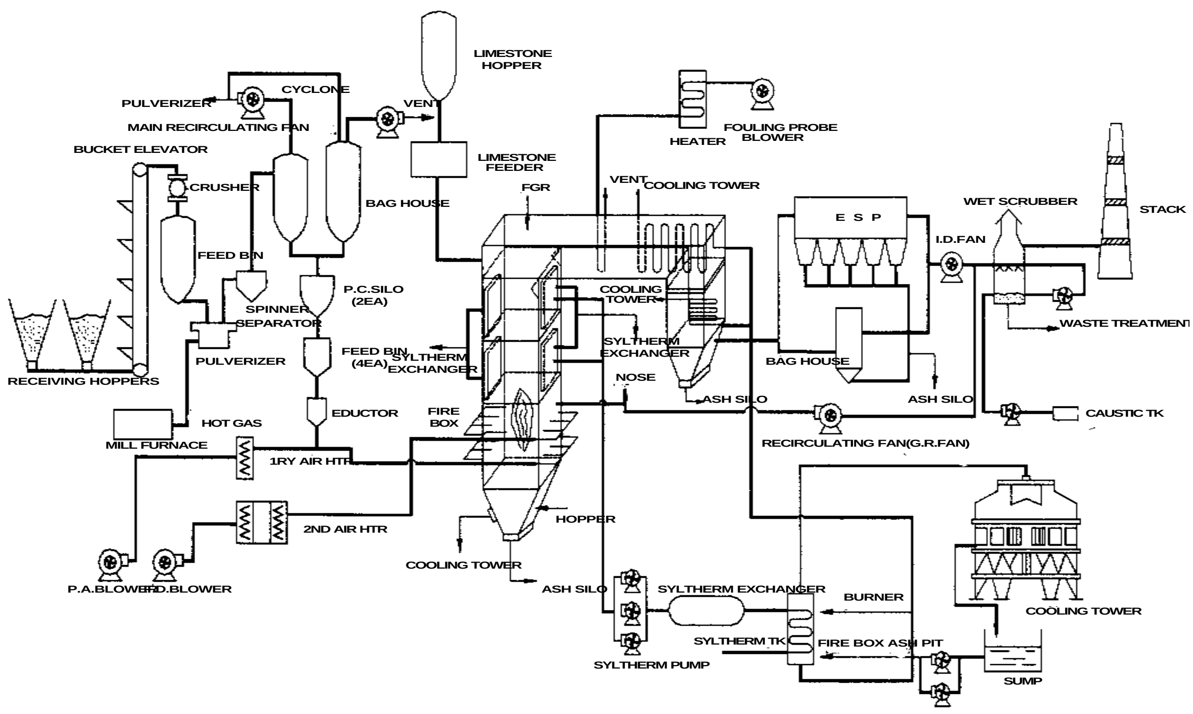

Fig. 1. Flow diagram for a pilot-scale combustion test facility.

parameters are listed in Table 1. Both heat and mass balances were performed to provide information to design the furnace [4]. The facility can be divided into three major systems; coal handling, burner and heat removal, and flue gas treatment systems. In addition, instrumentation and distributed control system is implemented.

Table 1. Impacts being investigated versus operation parameters.

Operation parameters	Impacts
Properties and chemical compositions of coals Pulverized coal fineness Combustion aerodynamics Fuel/Air ratio Sorbent injection	Pulverizer performance Flame stability and burnout Combustion efficiency Slagging, fouling, and heat transfer Erosion and corrosion Gaseous pollutant emission Particulate removal

1.1 Coal Handling System

Coal, with a diameter of less than 50 *mm*, is unloaded into one of two coal receiving hoppers. The volumetric rotary feeders independently control the feed rate of coal from each hopper. The coal is transported via a screw conveyor to a bucket elevator for pulverization. It is first crushed at the crusher to a top-size of 9.5 *mm*, stored in a feed bin temporarily, pulverized to 70 % by weight passing through a 200 mesh screen, and then stored in the silo. The pulverized coal is next transported by augers to any one of four feed bins connected to the gravimetric coal feeders. Each feeder, capable of feeding coals up to 70 *kg/hr* augers the pulverized coal to a downspout and eductor. The pulverized coal is then transported by the primary air to the splitter.

1.2 **Coal Burner and Heat Removal System**

Two kinds of coal burners can be installed; the moveable block swirl burners and the tangential burners, similar in concept to those developed by International Flame Research Foundation of Holland and Combustion Engineering of USA. The former can adjust the swirl number of secondary air from zero to two while the latter can change the tilting angle in the range from -20° to 20°. The burners can be arranged in three different modes, i.e., single-wall, opposed-wall, and tangential firing modes by changing the fire box. The burners are, therefore, mounted on the removable panels. During the single-wall firing, a panel with six burners, three burners in each row, is placed at the front wall of the furnace while in the opposed-wall firing mode, two panels with four burners each, two burners in each row, are placed at two walls opposite to each other. Thus, combustion aerodynamics in the furnace can be changed by varying the ratio of mass flow rates of the primary air to the secondary air, the swirl number and/or tilting angle, and the burner configurations. The primary and secondary air heaters are designed for the maximum temperature of 204. and 400., respectively. Two natural gas burners are located on two corners diagonally for preheating the furnace.

The inside of firebox is lined with refractory bricks to reduce the slagging on the walls. There are two layers of insulation between the brick and the steel plate shell that forms the furnace body. Above the firebox are two radiant sections that followed by the nose and the convection sections. There are slag panels, fouling probes, and heat exchangers from the radiant to convection sections to extract the combustion heat release that replace the steam generation components in real boilers such as superheater, reheater, and economizer. Temperature of the flue gas at the nose section and at the end of the convection section would be 1150. and 150., respectively. Below the firebox is a bottom ash hopper, and another hopper is at the end of the convection section to collect fly ash. A limestone injection nozzle is located at the nose section for the purpose of flue gas desulfurization. Other auxiliary equipment includes induced draft fan, gas recirculation fan, cooling tower, handy soot blower, emergency generator, compressors.

1.3 Flue Gas Treatment System

Flue gas coming out from the furnace flows through the stack via either an electrostatic precipitator or bag house and scrubber. The electrostatic precipitator and bag house are specified to remove 99 *%* of the fly ash from flue gas stream before the gas gets into the scrubber. The wet scrubber has a capability to remove SO_2 up to 3,000 *ppm* and HCl up to 500 *ppm*, uses caustic soda as the base, and is controlled by means of a PH controller. The scrubber sludge is discarded since there is very little solid material. Between the particulate removal system and the scrubber, there is the gas recirculation fan to send up to 25 % of the flue gas back into the furnace as tempering air.

1.4 Instrumentation and Distributed Control System

In operating the furnace, major process data such as the temperature, pressure, flow rate, and chemical concentrations are being measured by means of the corresponding sensors installed at proper places. Also, inside of the furnace, for example, coal flame shapes, are monitored by a CCTV mounted in the nose section. There are view ports at the various

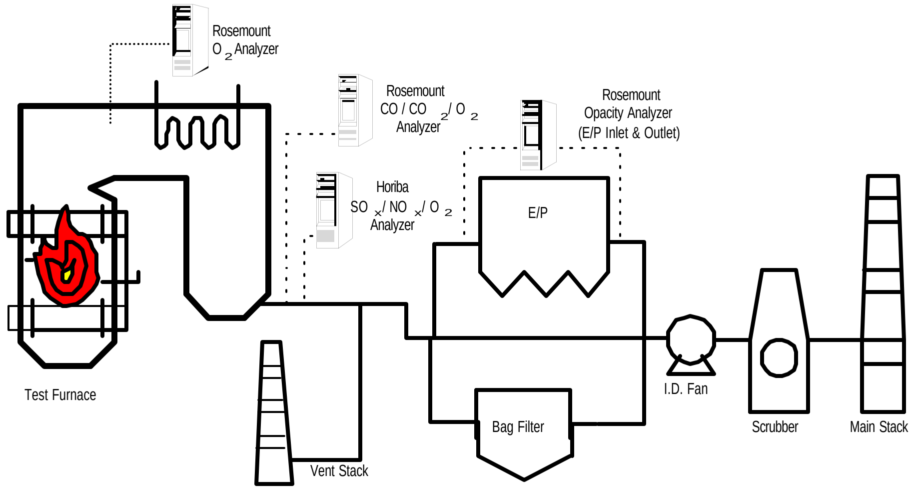

Fig. 2. Schematic diagram for installation of the opacity meters and gas analyzer

locations all over the facility for sampling and viewing purposes. The specimens to be sampled include the pulverized coal, bottom ash, fly ash, and flue gas. Two opacity meters are installed at the inlet and outlet of the particulate removal unit, and two gas analyzers to measure SO_X, NO_X, O_2, CO, and CO_2 concentrations are also installed near the end of the furnace. Installed positions of the opacity meters and gas analyzers are shown in Fig. 2. At the end of the convection section is a converging section that can accommodate erosion and corrosion made out of platinum foil. Two ultraviolet flame detectors are equipped as a part of the interlocks system of the furnace and aligned in such a way that they can detect a flame in any firing mode.

The facility can be operated automatically by means of the distributed control system, and also be in manual operation mode if needed. In auto mode, main process data are transferred from the local to the distributed control system via field bus network and let the distributed control system run the facility by itself. Another advantages of the distributed control system include its reliability and easy expandability.

2. COMBUSTION TEST PROCEDURE

In the test runs, the facility needs to be preheated up to 900 with natural gas burners. Then, a preliminary test of every single component of the facility is conducted to verify their performances during the coal firing. Some parametric studies can be conducted by varying the swirl number and the ratio of the primary to secondary airflow, *etc.* After all test runs, the furnace is cooled down and reach the inside temperature to the ambient.

During the tests, images of coal flames are videotaped and all the process data are stored into the distributed control system for the post-processing. For measuring temperature distribution inside the furnace, Thermocouples are set up as shown in Fig. 3.

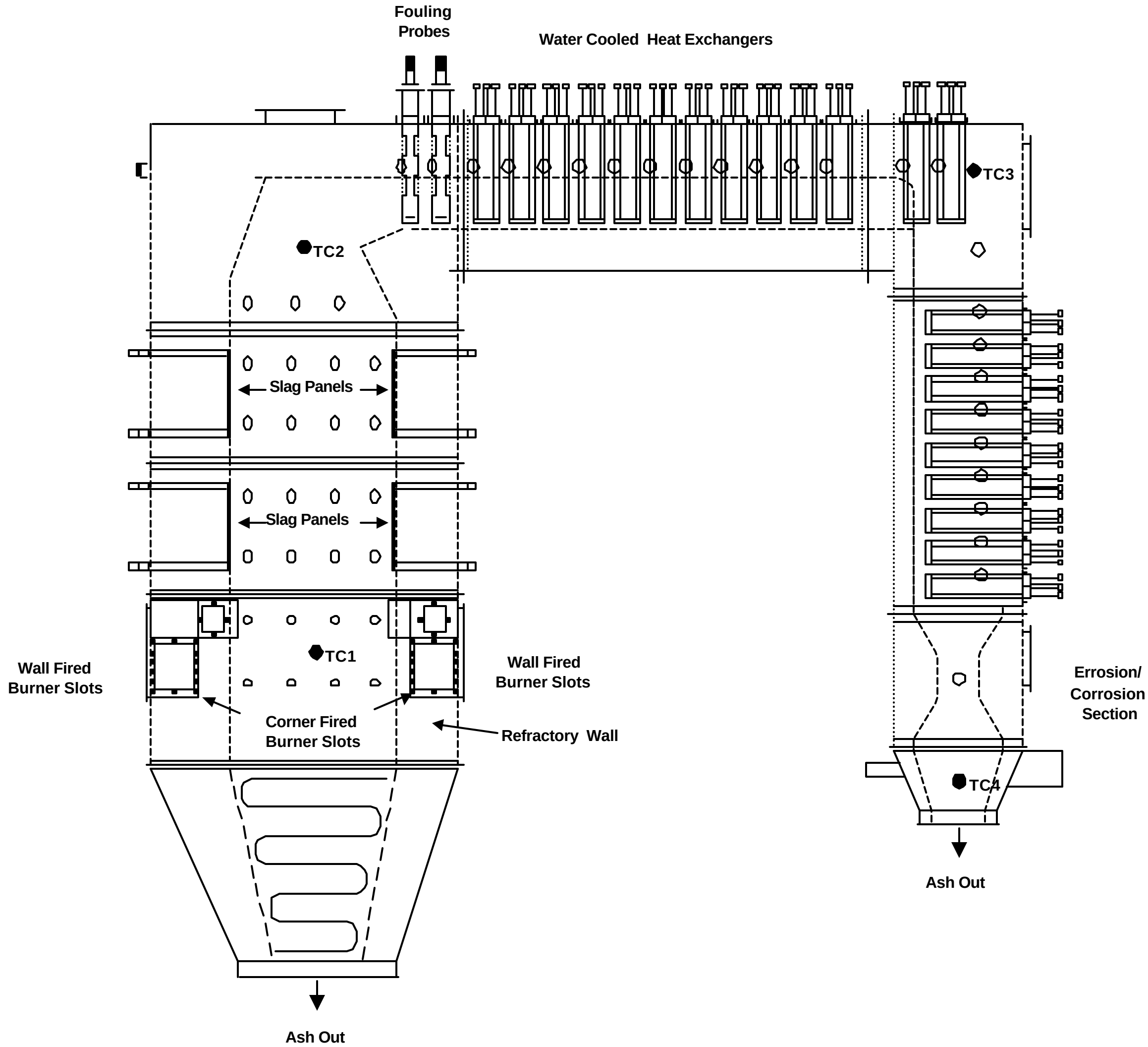

Fig. 3. Schematic diagram of the test furnace and locations of four major thermocouples.

Ash deposit on the fouling probe for a test is given in Fig. 4. As shown in the figure, the coal ash is deposited near the stagnation points of the fouling probe with diameter of 89 *mm* and length of 975 *mm*. Average fouling factor is defined as change of thermal conductivity of the fouling probe due to ash deposit, and is calculated as follows [5].

$$R_{f,avg} = \left.\frac{A_0 \Delta T_{lm}}{m C_{p,a}(T_{a,o} - T_{a,i})}\right|_{\text{with ash}} - \left.\frac{A_0 \Delta T_{lm}}{m C_{p,a}(T_{a,o} - T_{a,i})}\right|_{\text{without ash}} \qquad (1)$$

where $\Delta T_{lm} = \dfrac{(T_g - T_{a,o}) - (T_g - T_{a,i})}{\ln\left(\dfrac{T_g - T_{a,o}}{T_g - T_{a,i}}\right)}$

$R_{f,avg}$: Average fouling factor

A_o : Outer surface area of the fouling probe ($pD_oLN = 1.9\times10^6\ mm^2$)

D_o : Outer diameter of the fouling probe (89 mm)

L : Length of the fouling probe (975 mm)

N : Number of the fouling probe (= 7)

m : Flow rate of cooling air

$C_{p,a}$: Specific heat at constant pressure of cooling air

T_g : Temperature of flue gas

$T_{a,o}$: Outlet temperature of cooling air

$T_{a,i}$: Inlet temperature of cooling air

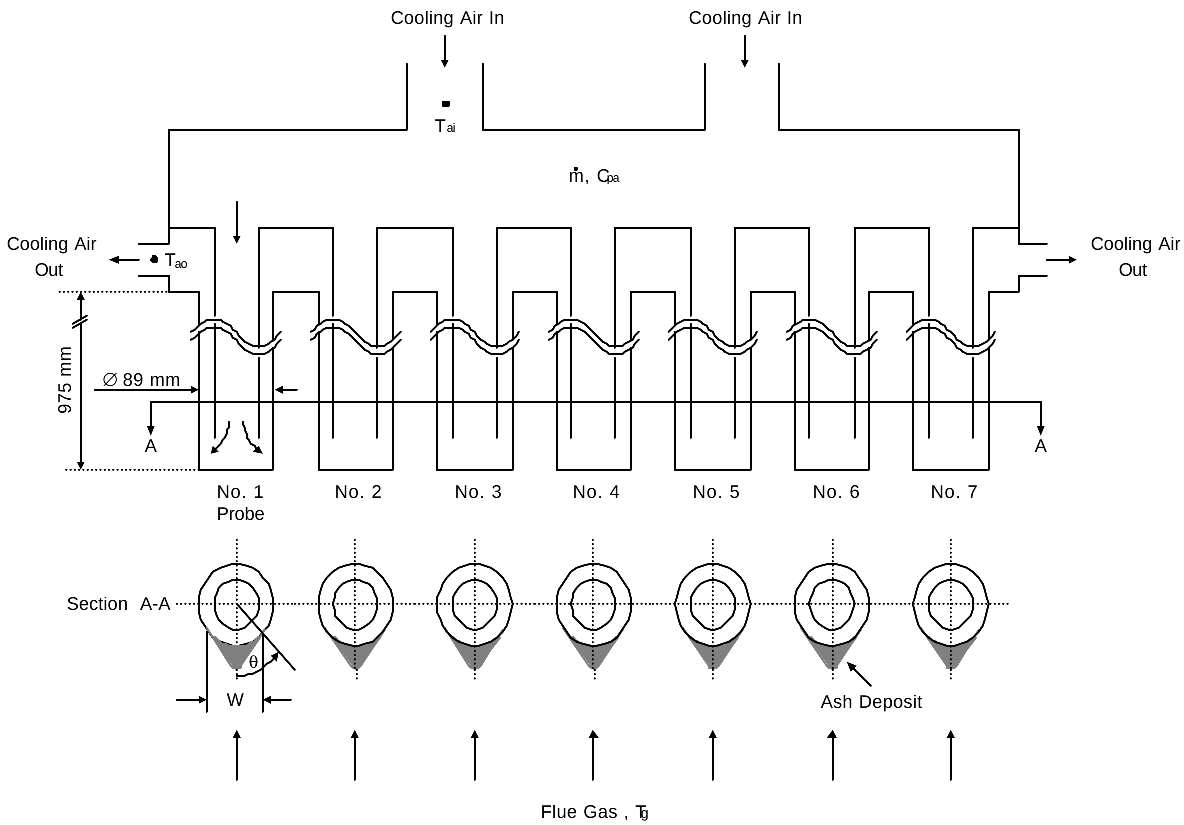

Fig. 4. Fouling probe and ash deposit on its seven tubes.

3. COMBUSTION TEST RESULTS

Prior to test run of the facility, the test coals are analyzed, and the results are shown in Table 2. According to the results, KIDECO coal, imported from Indonesia, has the characteristics of sub-bituminous coal that has fixed carbon content of 43.78 *%*, volatile matter of 39.62 *%*, and very high moisture. On the other hand, TOTAL coal, imported from South Africa, has the characteristics of bituminous coal that has fixed carbon content of 56.92 *%* and volatile matter of 27.01 *%*.

Table 2. Analysis of the test coal.

Property	KIDECO (Indonesia)	TOTAL (South Africa)
Proximate analysis (*wt %*)		
Moisture	14.24	2.71
Fixed carbon	43.78	56.92
Volatile matter	39.62	27.01
Ash	2.36	13.36
Calorific value (*kcal/kg*)	6,908	6,844
Hardgrove grindability index	53	50
IDT( )	1,218	1,325
Ultimate analysis (*wt %*)		
Carbon	69.20	72.78
Hydrogen	5.10	4.63
Oxygen	21.88	8.53
Nitrogen	0.97	1.31
Sulphur	0.19	0.65
Ash	2.76	12.10
Ash analysis (*wt %*)		
SiO_2	38.80	51.91
Al_2O_3	13.24	28.44
Fe_2O_3	20.33	7.42
CaO	12.60	1.04
MgO	2.57	0.50
Na_2O	0.13	0.16
K_2O	0.92	0.73
SO_3	9.03	7.93
The others	0.75	1.87

Table 3. Test conditions of blended coal

Operating condition	Blended coal (KIDECO 70 %, TOTAL 30 %)	
Coal feed rate (*kg/hr*)	180	
Pressure inside furnace (*mmAq*)	5	
Excess air ratio (*%*)	3.0	4.0
Cooling water flow rate (m^3/hr)	70	
Primary air flow rate (Nm^3/min)	6.7	7.1
Secondary air flow rate (Nm^3/min)	20.1	21.3
RPM of pulverizer	900	

Combustion tests were conducted using the blended coal at the ratio of KIDECO 70 *%* to TOTAL 30 *%* and operating conditions are given in Table 3. Coal feed rate is 180 *kg/hr* at the pressure inside the furnace of +5 *mmAq*, and combustion test runs are conducted by changing the excess air ratio, 3.0 *%* and 4.0 *%*.

In test runs, heat losses from the furnace at the excess air ratios of 3.0 *%* and 4.0 *%* were measured and the results are listed in Table 4. The amount of unburned carbon loss is decreased from 0.69 % to 0.64 % as the excess air ratio increases from 3.0 *%* to 4.0 *%*, therefore, heat loss of unburned carbon is decreased. However, increase of heat loss due to flue gas is greater than decrease of heat loss due to unburned carbon with the change of excess air ratio from 3.0 *%* to 4.0 *%*. As a result of comparison, total heat loss due to flue gas and unburned carbon is increased in proportion to the increase of the excess air.

Measured temperatures inside the furnace show a similar distribution for both cases. The temperatures are approximately 1,414 at the burner zone, 1,146 ~1,275 around the radiation zone and 1,050 ~1,130 at the nose of the furnace. Planar temperature distribution at the distance of 50 *cm* above the burner part is shown in Fig. 5. Measured temperature histories of flue gas after heat exchanger are given in Fig. 6. The results show that flue gas temperature increased from 100 to 170

Table 4. Comparison of heat loss.

Excess air ratio (%)	Flue gas		Unburned carbon		Sum	
	Heat loss (*kcal/kg*)	Heat loss ratio (*%*)	Heat loss (*kcal/kg*)	Heat loss ratio (*%*)	Heat loss (*kcal/kg*)	Heat loss ratio (*%*)
3.0	314.0	4.39	49.3	0.69	363.3	5.08
4.0	370.4	5.17	46.1	0.64	416.5	5.81

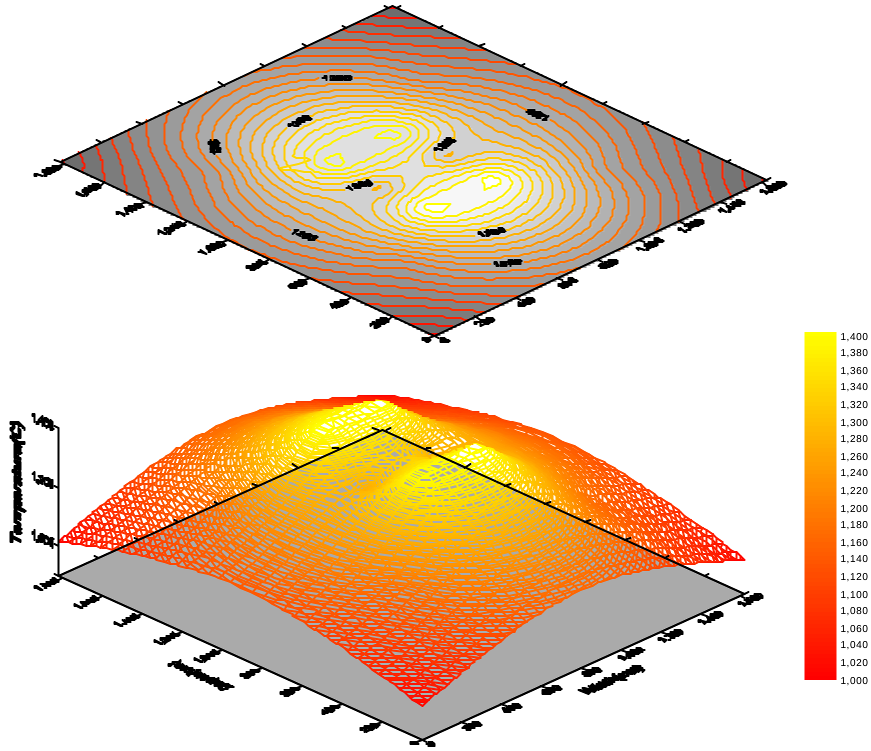

Fig. 5. Planar temperature distribution at the distance of 50 *cm* above burner zone.

Flue gas temperature increases by 10 as excess air ratio increases from 3.0 *%* to 4.0 *%*. Temperature of flue gas at the excess air ratio of 4.0 *%* is higher than that of 3.0 *%*, and this causes the increase in heat loss by flue gas.

To measure the environmental impacts, SO_X/NO_X analyzer and opacity meters are installed at the outlet of the furnace and the inlet/outlet of electrostatic precipitator (EP). The analytical results of opacity and SO_X/NO_X concentrations are listed in Table 5. From the results of EP inlet/outlet opacity, efficiency of electrostatic precipitator were estimated to be approximately 73 *%*. Opacities at the inlet/outlet of electrostatic precipitator increase with the excess air ratio. SO_X concentration is nearly constant, however, NO_X concentration increases approximately 50 *ppm* as the excess air ratio increases from 3.0 *%* to 4.0 *%*. Fouling probes, shown in Fig. 4, are installed at the nose part inside the furnace. Figure 7 shows the history of fouling factor, which is calculated by equation (1). The result shows that fouling factor increases slowly from 0.003 m^2K/W to 0.01 m^2K/W during the combustion time up to 260min., but after 260min., fouling factor increases suddenly and then gradually increase up to 0.02 m^2K/W .

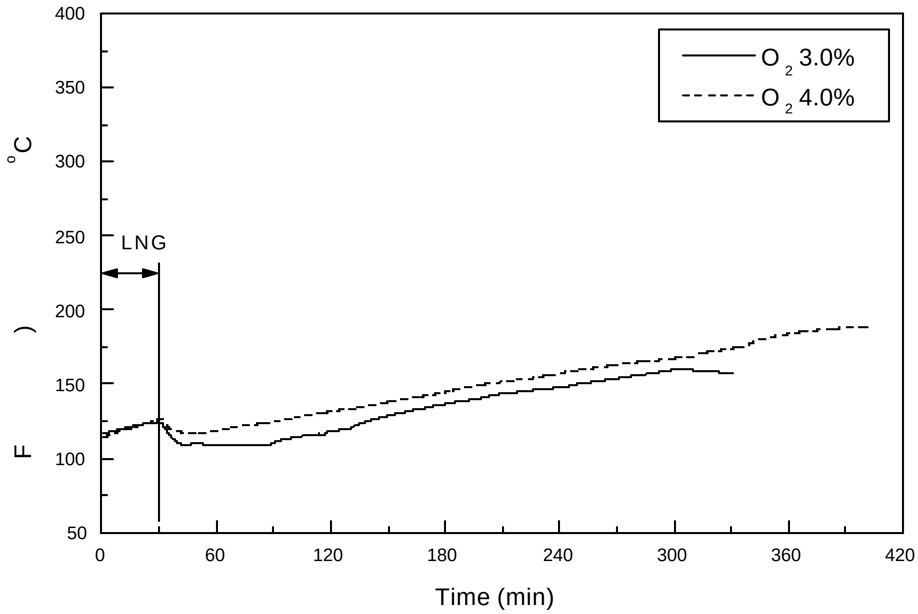

Fig. 6. Measured temperature histories of flue gas

Pulverizing characteristics of the blended coal is investigated at 900 *rpm* of pulverizer. Fineness levels of the pulverized coal are listed in Table 6, and the percent of pulverized coal coarser than 100 mesh (150 *mm*) is relatively low at 0.24 *%*. Relationship between power requirements and coal fineness is investigated in test runs, and the results are listed in Table 7. As RPM of pulverizer increases from 600 *rpm* to 900 *rpm*, electric consumption is increased from 0.36 *kWh* to 0.44 *kWh* and the fineness of pulverized coal increases, that is, coal percent passing 200Mesh (74*mm)* is increased from 63.3 % to 70.9 %.

Table 5. Comparisons of environmental impacts

Excess air ratio (%)	EP inlet opacity (%)	EP outlet opacity (%)	SO_X (*ppm*)	NO_X (*ppm*)
3.0	19.57	5.36	216	372
4.0	19.73	5.51	209	423

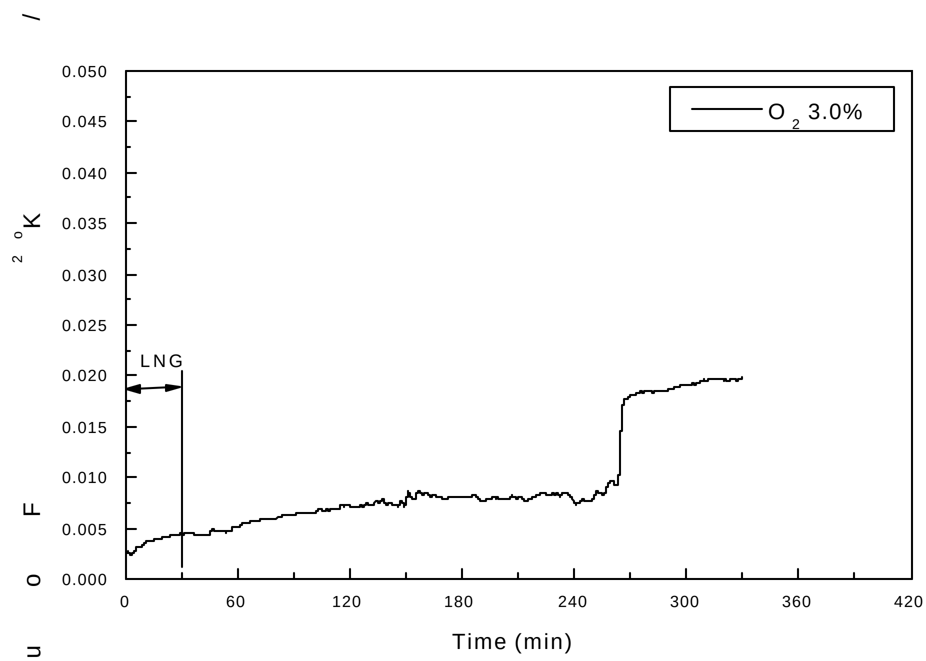

Fig. 7. History of fouling factor

Table 6. Pulverized coal fineness at 900 rpm of pulverizer

Sieve size (*mm*)	~ 44	44 ~ 74	74 ~ 104	104 ~ 150	150 ~
Sample wt. (%)	39.05	31.88	23.64	5.15	0.24

Table 7. Change of pulverized coal fineness with power required for pulverizer

Blended Coal Name	KIDECO (70 %) + TOTAL (30 %)			
Hardgrove grindability index	52			
Total moisture (%)	16.33			
RPM of pulverizer	600	700	800	900
Mass of pulverizing coal (*kg*)	200			
Electric power (*kWh*)	0.360	0.395	0.400	0.440
Required time for pulverizing(sec)	1,101	1,213	1,421	1,460
Sieve Analysis (% < 200Mesh)	63.3	64.2	66.4	70.9

4. CONCLUDING REMARKS

Combustion tests in the pilot-scale 1.6 *MW* combustion test facility have been conducted by blending two kinds of sub-bituminous and bituminous coals imported from Indonesia (KIDECO) and South Africa (TOTAL) at the ratio of seven to three. Coal feed rate is 180 *kg/hr* at the pressure inside the furnace of +5 *mmAq*, and combustion test runs are conducted at the excess air ratios of 3.0 % and 4.0 %. Total heat loss caused by flue gas and unburned carbon is increased by 0.83 % in proportion to the increase in the excess air ratio. The temperatures are approximately 1,414 at the burner zone, 1,146 ~1,275 around the radiation zone and 1,050 ~1,130 at nose of the furnace. Temperature of flue gas increases continuously and temperature of flue gas increases by 10 as excess air ratio increases from 3.0 % to 4.0 %. Opacities at the inlet/outlet of electrostatic precipitator increase with the excess air ratio. SO_X concentration is nearly constant, however, NO_X concentration increases approximately 50 *ppm* as the excess air ratio increases from 3.0 % to 4.0 %. Fouling factor increases slowly from 0.003 m^2K/W to 0.01 m^2K/W, and suddenly increases to 0.02 m^2K/W at around 260 *min*. combustion time. As RPM of pulverizer increases from 600 *rpm* to 900 *rpm*, electric power is increased from 0.36 *kWh* to 0.44 *kWh* and coal particles become finer, with increase in the percentage of -74 *mm* from 63.3 % to 70.9 %.

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