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Pressure Fluctuation Properties in Combustion of Mixture of Anthracite and Bituminous Coal in a Fluidized Bed

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Abstract−The combustion characteristics of a mixture of anthracite and bituminous coal were studied in a 0.155 m i.d. fluidized bed combustor (FBC). The properties of the pressure fluctuation for the bed such as the standard deviation, cross-correlation function, dominant frequency and the power spectral density function were obtained through statistical analysis. To interpret the combustion characteristics in the FBC with uniform or multi-sized particles of anthracite-bituminous coal mixture, the properties of pressure fluctuation were determined as a function of the particle size distribution and anthracite mixing fraction. In the present work, it is known that the combustion region could be obtained from the analysis of pressure fluctuation properties, and the mixed-firing of anthracite-bituminous coal is related to the reaction models of both coals and particle size distribution. Moreover, the relation between coal size distribution and static mean pressure, and the ignition region could be obtained from the mean pressure profile.

Key words: Combustion Characteristics, Pressure Fluctuation, Anthracite, Bituminous Coal, Fluidized Bed Combustor

INTRODUCTION

Anthracite coal is abundant in Korea, but its high ash content makes it inappropriate for use as an energy source [Jung and Park, 1988]. With the decrease in the amount of coal being used and an increase of expense of mining coal, the coal industry in Korea is in jeopardy. Therefore, utilization of coal is very important for mining protection and diversification of energy resource. For anthracite coal to be used more efficiently, the mixed-firing technology of bituminous and anthracite coal is very important. Among the various technologies, fluidized combustion has been applied extensively because it is not restricted by the type of coals and can control air pollution easily [Well et al., 1982]. The mixed-firing of various fuels in FBC has been carried out in previous studies: coal/sludge [Park and Son, 1990], coke/coal [Larva et al., 1989], and coal water mixture [Gregory and Brown, 1989]. The present study considered the effect of anthracite fraction on the characteristics of mixed-firing of Korean anthracite and an imported bituminous coal.

In this work, to interpret the combustion characteristics in a fluidized bed combustor of mixed anthracite and bituminous coal, the physicochemical analysis and the pressure fluctuation properties were measured as a function of the particle size ratio and the anthracite mixing fraction. In the meantime, the combustion characteristics of mixed fuels in the FBC could be interpreted by using pressure fluctuation properties such as standard deviation of pressure fluctuations, mean pressure and power spectrum density function. The different burning region of the FBC was measured by the pressure fluctuation properties.

EXPERIMENTAL

1. Experimental Apparatus

The experiments were performed with the facilities as shown in Fig. 1. The facilities consisted of an FBC and auxiliary systems (coal screw feeder, ash vibrating discharger, air preheater, cyclones, flue gas analysis systems and pressure measuring system). The cylindrical, stainless steel FBC has a total height of 2.1 m, inside diameter of 0.155 m up to 1 m, and is fitted with a perforated plate distributor (opening area 1.53%) having 1.0 mm holes arranged in a square pitch of 10 mm. The inner diameter of freeboard was expanded to 0.21 m with a height of 0.9 m to increase residence time of fine particles and volatile matter. The temperature of the FBC was controlled by heat-extracting equipment of horizontal heat exchanger tubes (1/4 in.) inserted into the bed. The exterior of the whole combustor was insulated heavily with ceramic wool to minimize heat loss. Combustion air supplied by a compressor was preheated with a 4.5 kW resistance heater to approximately 400 °C, which temperature was sufficient to ignite the charcoal fed for start-up. Anthracite coal and bituminous coal were continuously fed to the bed through i.d. 0.03 m pipe positioned 0.05 m above the distributor by spring type screw feeder, respectively. The mixing fraction of the fed coal depended on each feeding rate. Bed material of mainly coal ash was withdrawn through 3/4 in. pipe at the bottom of the bed by vibrating discharger to maintain a constant bed level.

Gas samples could be taken either from the flue gas before the first cyclone or within the combustor at several axial positions through the probes. These probes were positioned both in the freeboard and in the bed and were used to measure the axial profile of gas concentration. At the end of the probes, stainless steel mesh was ap-

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‡This paper is dedicated to Professor Dong Sup Doh on the occasion of his retirement from Korea University.

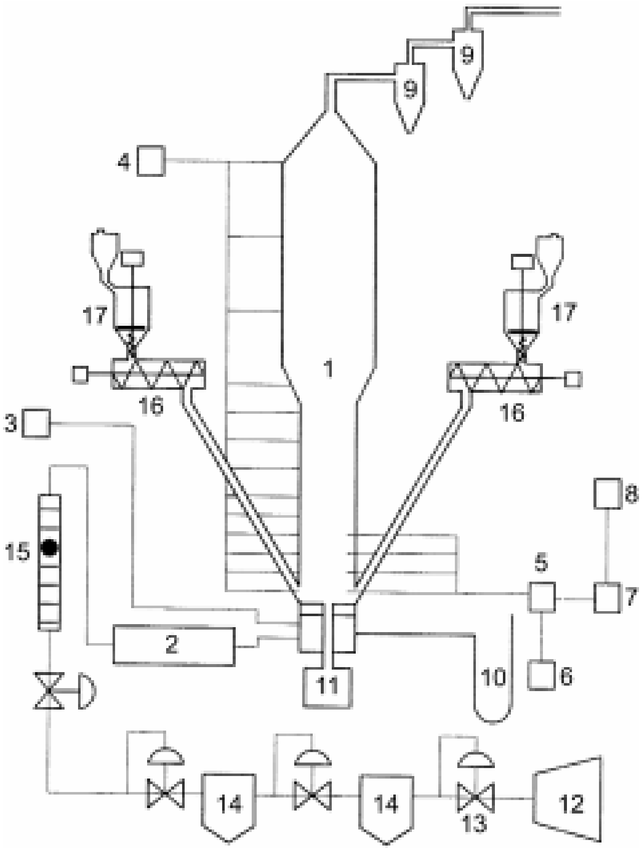

Fig. 1. Experimental facilities and data processing system at high temperature.

1. Fluidized bed combustor	10. Manometer
2. Preheater	11. Vibrating discharger
3. PID temperature controller	12. Air compressor
4. Digital multi-thermometer	13. Regulator
5. Pressure transducer	14. Air filter
6. Power supplier	15. Flow meter
7. Amplifier	16. Screw feeder
8. Data acquisition system	17. Hopper
9. Cyclone	

plied to prevent solid particles from entering the tube. The gas samples withdrawn from the combustor or the exhaust were analyzed for CO_2, CO, SO_2 and O_2 by using three infrared and one paramagnetic analyzer, respectively. Also, hydrocarbons among the flue gas were analyzed by gas chromatograph (HP 5890). The combustion gases pass primary and secondary cyclones, and then are vented.

Four pressure taps were mounted on the wall of the FBC; the distance between two adjacent taps was 50 mm. The pressure probe was inserted in the middle of the bed through the pressure tap. The pressure probe, which was immersed in the fluidized bed combustor, was made of a stainless steel tube of 4 mm in diameter and 0.5 m in length. One end of the tube was covered with a 400-mesh screen to prevent the solid particles from entering the probe, and the other end was connected to the pressure transducer. Four transducers with working capacity of 1.0 psi were used for the accuracy and simultaneity of the measuring values. A personal computer with a 12 bit A/D converter was installed for the calculation and digitization of measured pressure fluctuation signals.

2. Experimental Procedure

Table 1. Analysis of coals

	Proximate analysis (wt%)					
	Moisture		Volatile matter	Fixed carbon		Ash
Anthracite	1.8		6.5	27.0		64.7
Bituminous	6.7		27.5	57.4		8.4
	Ultimate analysis (wt% on dry basis)					
	Carbon		Hydrogen	Oxygen	Nitrogen	Sulfur
Anthracite	30.0		0.7	4.2	0.3	0.3
Bituminous	72.3		4.3	11.7	0.4	0.2
	Ash analysis					
	SiO_2	Al_2O_3	Fe_2O_3	K_2O_3	TiO_2	MgO
Anthracite	53.0	28.2	2.7	3.9	1.3	1.9
Bituminous	65.5	27.9	2.2	1.4	1.5	0.4

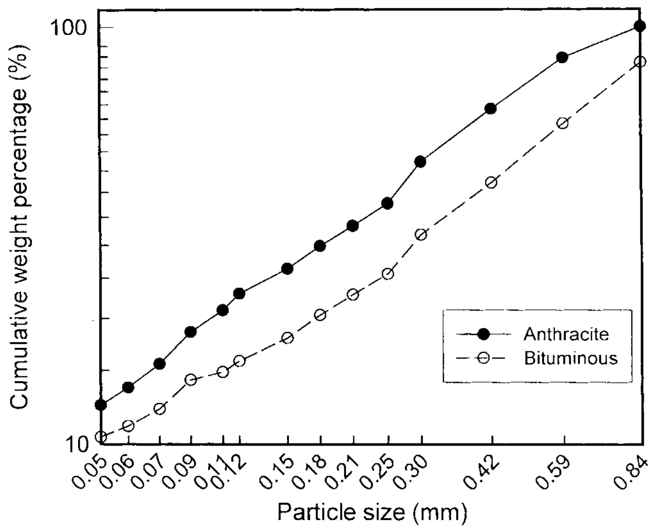

Fig. 2. Size distribution of coal samples.

The initial bed was charged with anthracite coal ash with aspect ratio (L/D) of about 1.0. The bed was fluidized by preheated air, and charcoal was fed when the bed temperature reached 400 °C. Bituminous and anthracite coal was supplied when the bed temperature arrived at 600 °C and 800 °C, respectively. The composition of flue gases was analyzed continuously by the flue gas analyzers (MCSAM - 2000Z, KIMOTO Co.). The coals used in the experiments are a bituminous coal from Australia and low-grade domestic anthracite. Their analyses and size distributions are given in Table 1 and Fig. 2, respectively. The coals were fed into the FBC continuously. When the operation of the FBC attained equilibrium, the pressure fluctuation at each of the four points was measured by the pressure transducer. From a single recorded data variable X(t), the mean value and the standard deviation of pressure fluctuations representing the fluctuating property and static pressure can be expressed respectively as [Bendart and Piersol, 1971; Cooper and McGillem, 1971].

$$\mathrm{S.D.} = \left[\lim_{T\to\infty}\frac{1}{T}\int_0^T (X(t)-\mu_x)^2 dt\right]^{1/2} \quad (1)$$

Table 2. Operating conditions

Air velocity (m/sec)	Initial in-bed particle size (mm)	Bed temperature (°C)	Aspect ratio (L/D)	Anthracite fraction	Excess air (%)
0.304	Multi-sized, 0.715	900	1.0	0.0-1.0	20

$$\mu_x = \lim_{T\to\infty}\frac{1}{T}\int_0^T X(t)dt \quad (2)$$

$$G_x = 2\int_{-\infty}^{\infty} R_x(\tau)\exp(-i2\pi f\tau)dr \quad (3)$$

The experimental conditions are given in Table 2. The used domestic anthracite coal has a heating value of 2,010 kcal/kg and the imported high-calorific bituminous coal has a heating value of 6,520 kcal/kg.

RESULTS AND DISCUSSION

In order to investigate the combustion characteristics of the mixed fuels of bituminous and anthracite coal, first, the activation energy and ignition time of the coals were examined in the FBC as shown in Figs. 3 and 4. The activation energy was obtained by thermogravimetric analysis [Coats and Redfern, 1964]. Fig. 3 shows the activation energy of coal mixture with the variation of the anthracite mixing fraction. It was known that the activation energy of anthracite coal is higher than that of bituminous coal, and the activation energy increases with increasing anthracite mixing fraction. The ignition time is defined as the time the batch fluidized bed arrived at the maximum temperature [Kato and Wen, 1969]. The temperature profiles were measured to determine the ignition time of coal mixture in a batch fluidized bed combustor. When the batch fluidized bed approached steady state, coal sample particles were injected to the bed and then temperature profiles were recorded by personal computer. The ignition time with the variation of the anthracite mixing fraction is shown in Fig. 4. As can be seen in this figure, the ignition time increases with increasing anthracite mixing fraction. For pure anthracite coal, the ignition time is 135 sec. It means that the activation energy of anthracite coal is higher than that of bituminous coal, and anthracite coal can be burned slowly.

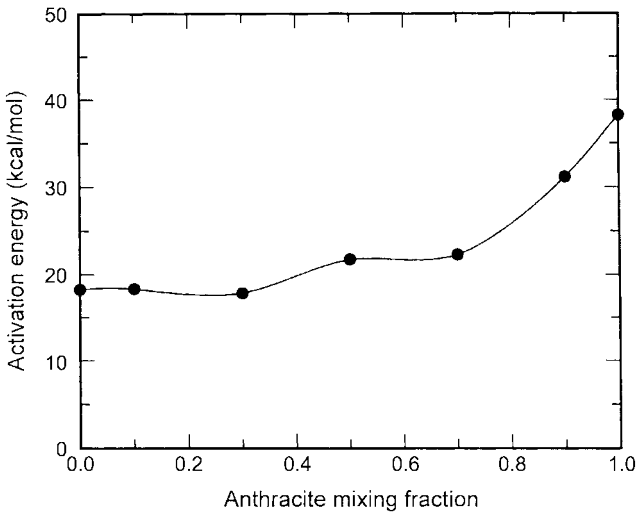

Fig. 3. Activation energy with anthracite mixing fraction.

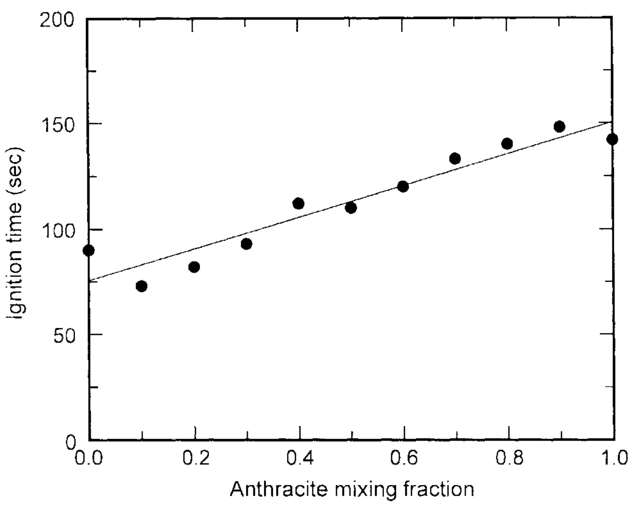

Fig. 4. Ignition time with anthracite mixing fraction.

1. Coal System of Anthracite with Two Different Sizes

The experiment was performed under the operation conditions of 20% excess air, 0.304 m/sec air velocity, and 900 °C bed temperature, varying anthracite fraction. If the bed is fully fluidized, then the pressure drop of the in-bed region according to bed height of the axial position is as follows:

$$\frac{dP}{dh} \propto -\rho \quad (4)$$

If the binary system of a cold fluidized bed is segregated, the axial pressure drop value differs from the positions of the bed. The pressure drop of equal distance of the bed is the same as that of the uniform particle system. Those values are not related to the measuring height of the axial position. In an FBC system, however, the pressure drop values are not equal according to the measuring height above the distributor. The coal combustion occurs in the upper region of the bed. The effectiveness density of burning coal particle is decreased by gas film. Therefore, the pressure drop values of the upper region are not same as those of the lower region.

Fig. 5 shows the pressure drop according to axial position of the fluidized bed in the binary coal particle system. In this figure, the coal mixture consists of jetsam (anthracite coal of 0.715 mm) and flotsam (anthracite coal of 0.359 mm). The pressure drop profile of the in-bed region is increased with increasing flotsam coal mixing fraction. The binary coal particle system is denser than a uniform coal particle system. Thus, the pressure drop crossing the in-bed region is increased. Such a result can be anticipated on bed voidage which decreased with mixing of binary coal particles. The difference in pressure drop value according to bed region will arise from moving of the combustion region.

The standard deviation of pressure fluctuation crossing the two points of the bed is shown in Fig. 6. As can be seen in this figure,

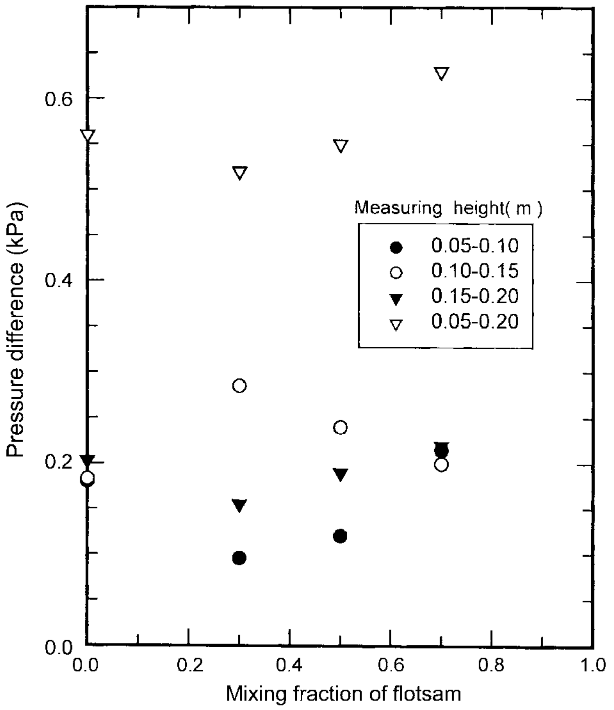

Fig. 5. Pressure difference according to mixing fraction of small anthracite coal (Jetsam: 0.715, flotsam: 0.359 mm).

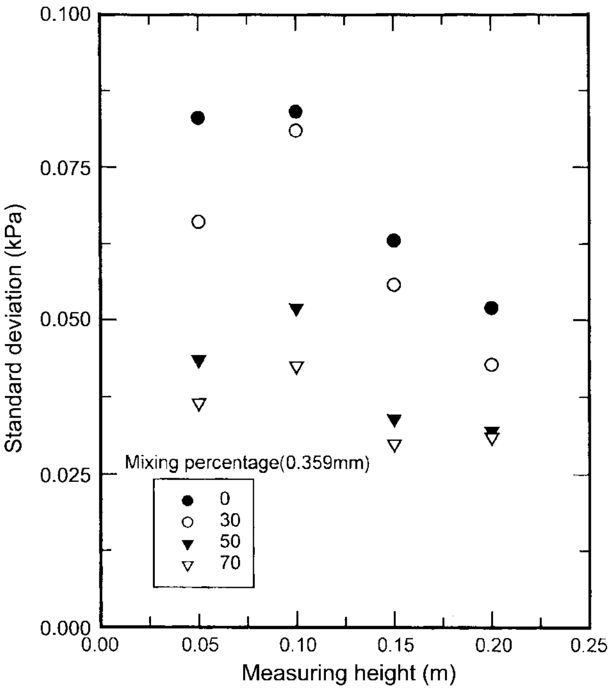

Fig. 6. Standard deviation of pressure fluctuations along the axial position of the bed.

the values of the standard deviation profile change with flotsam coal mixing fraction. This value of pressure fluctuation at 0.1 m above the distributor is larger than the other one. The reason is that the coal feeding height was positioned at 0.05 m above the distributor in this experimental apparatus. Thus, gas evolution and ignition took place at 0.1 m above the distributor.

2. Binary System of Anthracite and Bituminous Coal with Uniform Particle Mixture

Fig. 7 shows the standard deviation of pressure fluctuation val-

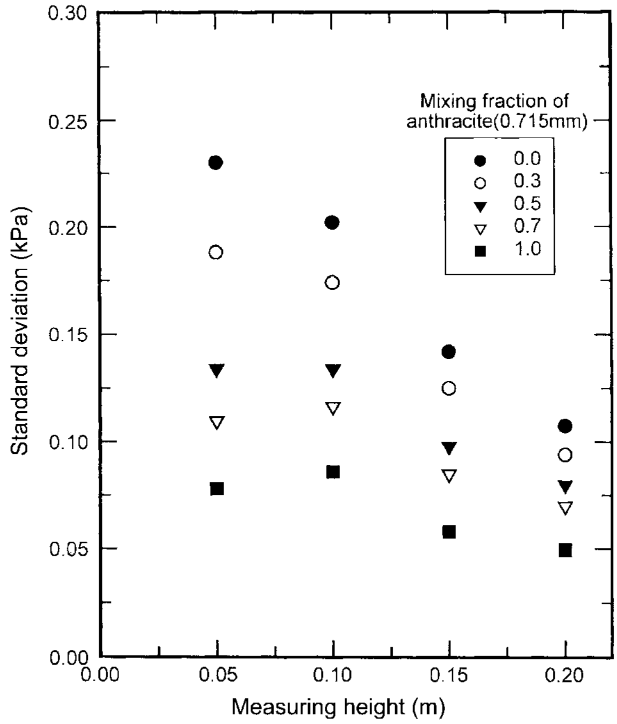

Fig. 7. Standard deviation of pressure fluctuations with mixing fraction of anthracite along the axial position of the bed.

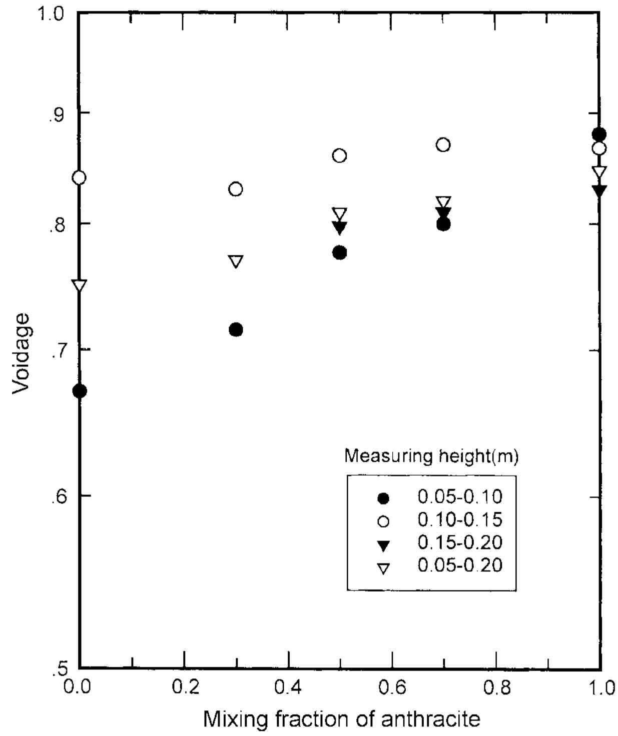

Fig. 8. Voidage according to anthracite mixing fraction (using anthracite and bituminous coal size: 0.715 mm).

ues according to axial position of the fluidized bed related with the mixing fraction of anthracite on the mixed-firing of an anthracite and a bituminous coal. The mixture consists of jetsam coal particle (anthracite coal of 0.715 mm) and flotsam coal particle (bituminous coal of 0.715 mm). In a binary particle system with different size, the values of the standard deviation of pressure fluctuation at 0.1 m above the distributor are larger than the other one. In a binary particle system with different coal, however, the values of standard deviation of pressure fluctuation are different from that of the binary particle system with different size. This value on the bottom of the bed is larger than the other region, and increases with decreasing anthracite mixing fraction. The different forms of coals, a bituminous coal with high volatiles content, give porous chars whose combustion is rapid; anthracite, however, gives solid carbon char whose combustion is relatively slow. Therefore, the combustion region moves toward the bottom of the bed; the maximum value of standard deviation of pressure fluctuation appears in the bottom region. In considering the combustion characteristics of mixed-firing with different coal type, it is known that the changing region of the combustion and the relationship between standard deviation of pressure fluctuation and combustion can be related to the mixing of burning coal particles.

In the meantime, the bed voidage according to anthracite mixing fraction is increased as shown in Fig. 8. The bed voidage at the point 0.10-0.15 m above the distributor is larger than the other region. This result indicates that the ignition occurs near the coal feeding point and the coal particle begins to evolve at that point. The anthracite coal burns with unreacted core model, which moves to the splash region with ignition. But the burned anthracite particles are sunk to the bottom of the bed, where combustion of unburned anthracite occurs. Therefore, the bed voidages of the upper region are not same as those of the lower region. Thus, the bed voidage values according to axial position of the bed are related with coal particle mixing and burning in the binary coal particle system with different types.

The effects of mixed-firing to power spectrum distribution for the bed height above the distributor are shown in Fig. 9. The motion of bubbles is the major factor of the pressure fluctuation in a fluidized bed [Kim et al., 2002]. It is known that analysis of power spectral density function is a basic method for interpreting the fluidized bed behavior. The frequency corresponding to the maximum power in the spectrum is called the dominant frequency. The power

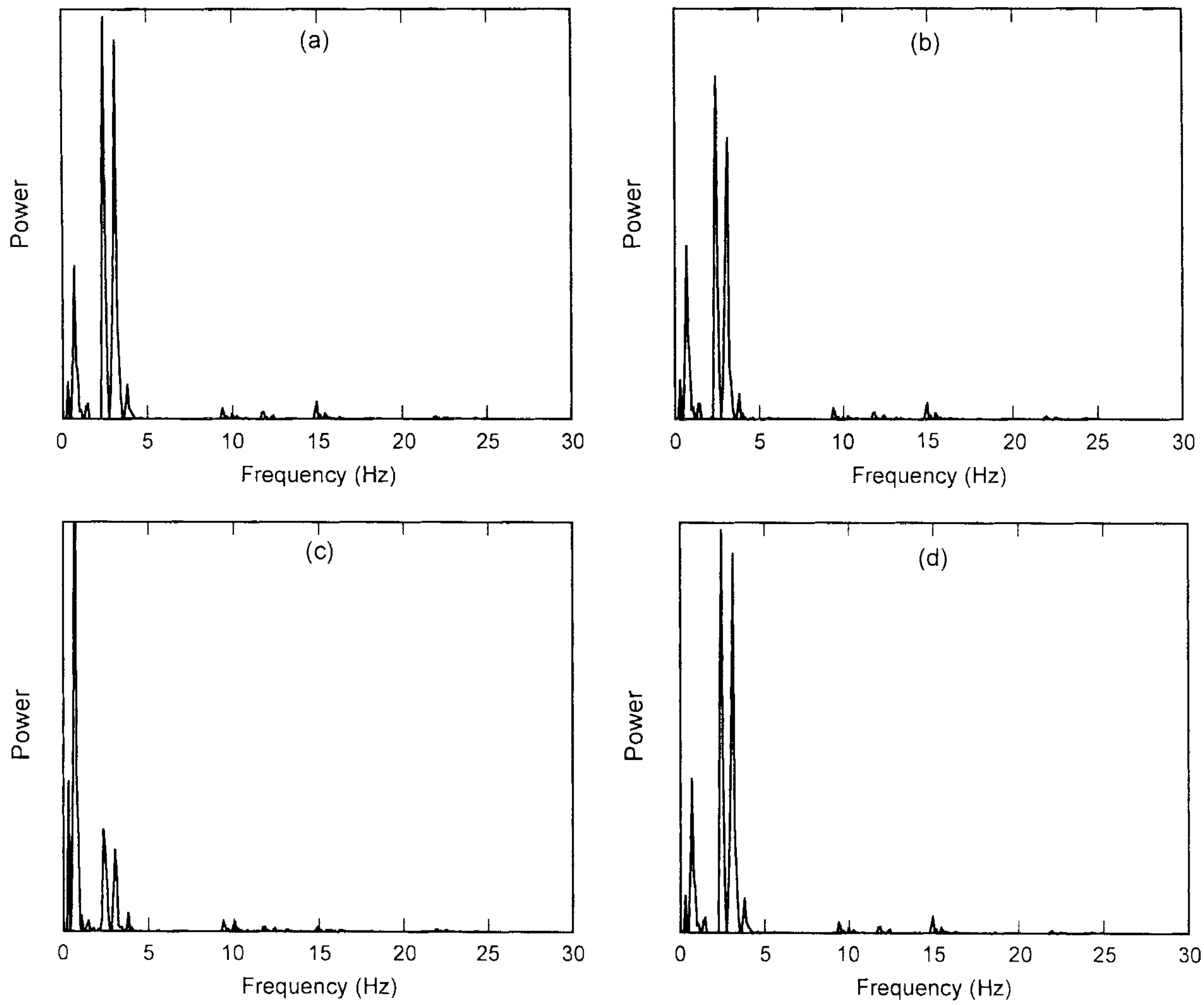

Fig. 9. Power spectrum distribution according to measuring height [(a) 0.05, (b) 0.10, (c) 0.15, and (d) 0.20 m; anthracite mixing ratio, X_a=0].

spectrum distribution shows the distribution of energy with the frequency and amplitude of pressure fluctuation. Thus, the narrow spread of the frequency spectrum represents the existence of periodic components in the pressure fluctuations, that is, the bubble formation or bubble passage occurs very regularly at the measuring position of pressure fluctuations. The wide spread of frequency spectrum, on the contrary, is considered as the case of either bubble coalescence or complicated bubble motion. As can be seen in Fig. 9, the major spectrum of power spectrum distribution at 0.15 m appears at 0.5 Hz. However, for the other region, the major spectrum of power spectrum distribution is 3-4 Hz. We speculated that gas evolution and ignition have occurred at 0.15 m above the distributor. The frequency of 0.5 Hz is very slow; it does not appear to be affected by the fluctuation. The cold fluidized bed is not shown 0.5 Hz [Poersch et al., 1988].

3. Binary System of Multi-sized Particle Mixture with Anthracite and Bituminous Coal

In the cold system, the mean pressure with uniform density and size is a linear function of bed height in a freely bubbling region. In the binary particle system, the mean pressure profile according to bed height incurred transition because the degree of mixing had changed the voidage and the mixing, which related to bubble frequency and size. The mean pressure results on the mixed-firing with uniform coal mixture agree with the binary particle system in the cold bed. Nevertheless, as shown in Fig. 10, the mean pressure profile changes at 0.15 m above the distributor. The mean pressure profile is waved along the bed height. The value of mean pressure at 0.15 m above the distributor is larger than that of uniform coal system. For the particle system with multi-sized coal, the mean pressure profile shows the waved shape regardless of the anthracite mixing fraction. The wave shape of the mean pressure profile does not appear in any other particle system. The fine coal particles affect the value of mean pressure at 0.15 m above the distributor. Considering the combustion of fine coal particle, it is known that the increasing of static mean pressure, the relationship between gas evolution and mean pressure, can be related to the combustion region.

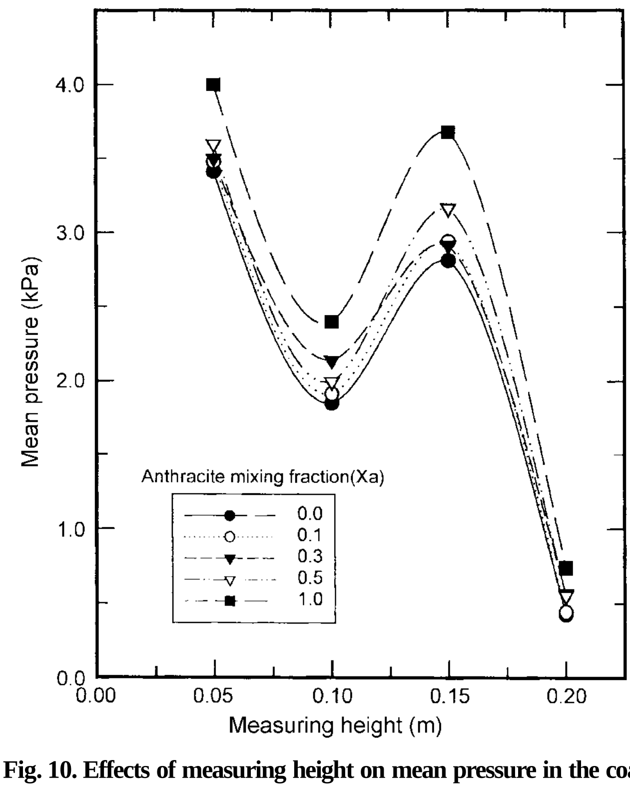

Fig. 10. Effects of measuring height on mean pressure in the coal combustor with the variation of anthracite coal mixing fraction.

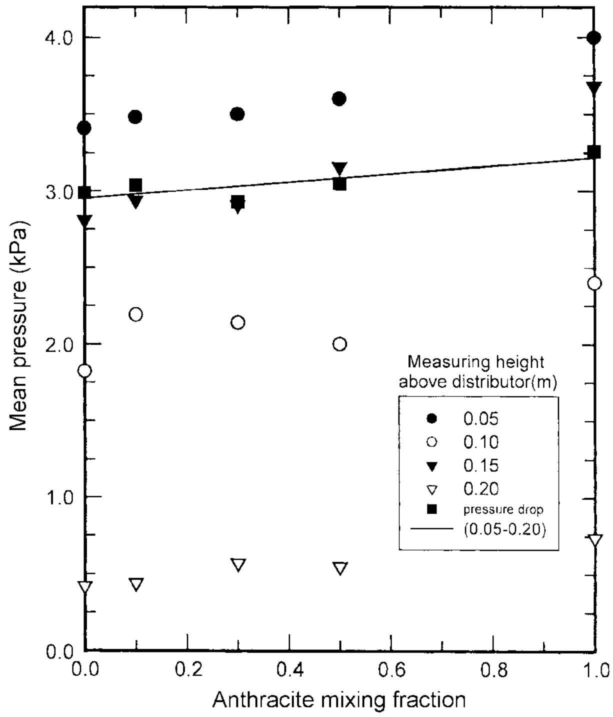

Fig. 11. Effects of measuring height on mean pressure and pressure drop across the in-bed region.

The static mean pressure and pressure difference across the bed are shown in Fig. 11. Bituminous coal burned with the shrinking core model is burned in the whole bed, and most particles become elutriated after burning. However, for anthracite coal burned with the unreacted core model, the anthracite particles are initially burned at the upper region of the bed, and residue carbon is burned at the in-bed after burning. Thus, the pressure drop across the bed is increased with increasing anthracite mixing fraction. The results indicate that bituminous coal with high volatiles content is burned in the upper region of the bed. Thus, it is found that the combustion region is obtained from the pressure difference profile and mean pressure.

CONCLUSION

The relationship between the characteristics of mixed-firing of an anthracite and a bituminous coal and the pressure fluctuation properties were examined in an FBC. Experimental data obtained from the pressure fluctuation properties and combustion characteristics of binary coal systems with particle size distribution and coal type show the following trends.

1. It is known that the combustion region could be obtained from the analysis of pressure fluctuation properties such as standard de-

viation of pressure fluctuations, mean pressure, and power spectrum distribution. The mixed-firing is related to the reaction model of coal and the particle size distribution.

2. The relation between coal size distribution and static mean pressure, and the ignition region could be obtained from the mean pressure profile.

NOMENCLATURE

D : bed diameter [m]
d_p : mean particle diameter [mm]
f : frequency [Hz]
$G_x(f)$: power spectral density function [-]
h : height above distributor [m]
L : static bed height [m]
P : pressure [kPa]
$R_x(\tau)$: auto correlation function [-]
S.D. : standard deviation [kPa]
T : observation time [sec]
t : time [sec]
X(t) : sample time history of time, t [sec]
X_a : anthracite mixing fraction [-]

Greek Letters

τ : space time [sec]
μ_x : mean pressure [kPa]
ρ : particle density [kg/m^3]

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