COAL COMBUSTION CHARACTERISTICS IN A CIRCULATING FAST FLUIDIZED BED

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(Received 3 December 1983 • accepted 14 January 1984)

Abstract—The effect of coal size (0.73-1.03 mm), excess air ratio (1.0-1.4), operating bed temperature (750-900°C), coal feeding rate (1-3 kg/h), and coal recycle rate (20-40 kg/h) on combustion efficiency, temperature profiles along the bed height and flue gas composition have been determined in a bubbling and circulating fluidized bed combustor (7.8 cm-ID × 2.6 m-high).

Combustion efficiency increases with increasing excess air ratio and operating bed temperature and it decreases with increasing particle size in the bubbling and circulating fluidzing beds. In general, temperature profiles and combustion efficiency are more uniform and higher in a circulating bed than those in bubbling bed. Combustion efficiency also increases with increasing recycle rate of unburned coal in the circulating bed.

The ratio of CO/CO_2 of flue gas decreases with increasing bed temperature and excess air ratio, whereas the ratio of $O_2/(CO+CO_2)$ decreases with bed temperature in both bubbling and circulating fluidized beds.

As a result of oil crisis, coal combustion in fluidized bed combustor have been a subject of worldwide interest in recent years. The low grade coals can be utilized for industrial and utility power generation, whereas the higher grade coals shall preferentially used for petrochemical feedstocks, synthetic fuels and metallugical processes.

A number of new techniques are being developing for utilization of coal in combustion processes. One of these is a circulating fluidized bed [1-3].

The conventional fluidized bed must operate with gas velocities which can only be varied from the minimum fluidizing velocity to the particle terminal velocity. Whereas a circulating fluidized bed can be operated with much higher gas velocity since the entrained particles are separated from the hot gas in a cyclone collector and recycled into the combustor. In addition, it has been claimed that a circulating fluidized bed can accomodate caking coals without pretreatment, high throughout capacity and it produce higher combustion efficiency and higher specific thermal load per unit cross section with low NO_x emmission.

Therefore, in this study, the effects of coal size, excess air ratio, operating bed temperature, coal feeding and recycle rates on combustion efficiency, temperature profiles along the combustor height and flue gas compositions have been determined in the bubbling and circulating fluidized beds.

EXPERIMENTAL

The coal used were either 0.73 mm (0.601-0.894 mm) and 1.03 mm (0.894-1.17 mm) bituminous coal with density of 1.4 g/cm³. The chemical analysis of the coal is given in Table 1.

Experiments were carried out in a stainless steel col-

Table 1. Properties of Coal tested

China Coal		
Calorific Value, Kcal/Kg	6,900	
Proximate Analysis, % on dry basis	Fixed Carbon	59.0
	Volatile Matter	29.2
	Ash	11.8
Ultimate Analysis, % on dry basis	Carbon	75.3
	Hydrogen	4.
	Oxygen	6.7
	Nitrogen	1.2
	Sulfur	0.6
	Ash	11.8

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umn of 7.8 cm-ID × 260 cm-high as shown schematically in Figure 1.

The coal particles were supported on a bubble cap distributor which contained 7 bubble caps in which 6 × 3.0 mm in diameter holes were drilled around the each bubble cap. The distributor was situated between the main column and air distributor box into which air was introduced through a 2.54 cm pipe. Oil free compressor air was fed to the column through a pressure regulator, filter and calibrated rotameter.

The coal was fed into the combustor by means of a volumetric screw feeder (Acrison, model 105-Z) with variable speed controller.

The pressure taps were mounted flush with the wall of the column at the elevation of 7,27,52,72,92,140,180 and 231 cm from the distributor plate. The static pressure drop at each of these points was measured with a water manometer.

Bed temperature was measured with Chromel-Alumel thermocouples which are connected to a digital thermometer (Omega-model 199) at eight different elevation points. The main bed temperature was controlled during the combustion operation by means of cooling tube which is situated in the middle of the combustor.

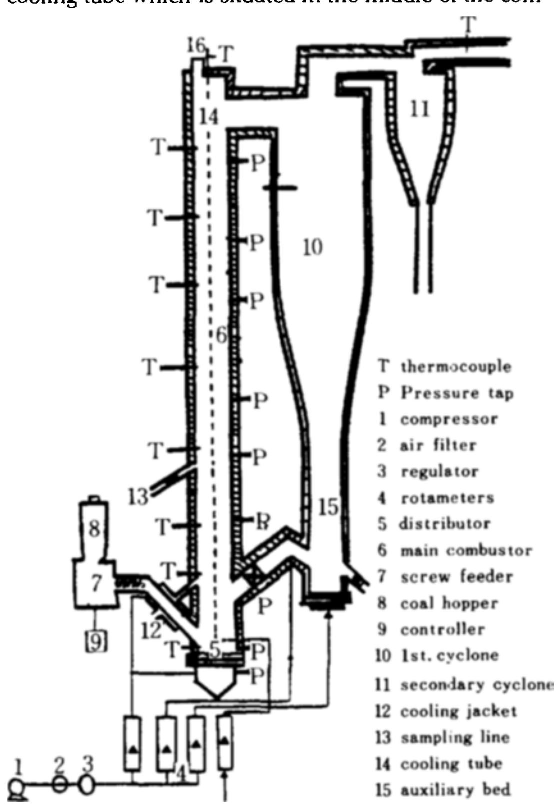

Fig. 1. Experimetanl Equipment

The entrained coal particles from the main column were captured in the first (19 cm-ID × 130 cm-high) and second (13 cm-ID × 52 cm-high) cyclones. An auxillary bed (7.8 cm-ID × 90 cm-high) with an air distributor at the bottom of the bed was attached to the bottom of the first cyclone as a feeding hopper for recycle the entrained particles. The recycle line was connected from the auxillary bed at 7 cm above the distributor to the main column at 10 cm above the distributor. The recycle solid rate was measured by means of a venturimeter in the recycle line. Two sampling ports were mounted on the wall of the main bed at the elevation of 45 and 95 cm from the distributor.

The main bed was heated to the desired ignition temperature of the coal by using the Kanthal line heater. The combustor was insulated by Kaowool ceramic fiber.

The combustor was initially loaded with 1.25 Kg of coal and 1.25 Kg of sand. As soon as the bed temperature rosed beyond the ignition temperature of the coal, the heater was turned-off and the desired flow rates of air and coal were maintained for the steady operation. The combusted ash was removed as the same rate of coal feeding rate through the sampling port.

In the circulating fluidized bed operation, the solids recycle rate was measured by venturimeter and its rate was regulated by the air flow rate in the auxillary bed and the recycle line.

The flue gas composition (CO, CO_2 and O_2) have been measured by using a gas analyser (Milton, Model 621A) at the steady-state operation. Experimental variables and the size distribution of the coal are given in Table 1.

RESULTS AND DISCUSSION

The combustion efficiency, E, in percentage of the coal samples can be defined as

$$E = 100\left[1-\left(\frac{A}{100-A}\right)\left(\frac{100-a}{a}\right)\right] \qquad (1)$$

in which A and a are the percentage of ash content in the original coal and in the refused coal, respectively. The a is the mean value of the samples taken from the combustor at the two different locations (45 and 95 cm-height).

Effect of Bed Temperature

In order to determine the effect of bed temperature on combustion characteristics, the operating bed temperatures were varied from 750-900°C in bubbling and circulating fluidized beds. As can be seen in Figure 2 that combustion efficiency increased with bed temperature in all the cases studied. Since the molecular chain of coal is known to be easily disrupted with increasing temperature[5] and consequent high reaction rate between oxygen and coal[5]. The rate of increase in combustion efficiency is more pronounced in bubbling bed than that in circulating fluidized bed since the bed voidage is much higher in circulating bed than that in bubbling fluidized bed.

Typical temperature profiles along the bed and freeboard heights in bubbling and circulating fluidized beds are shown in Figure 3. As can be seen the figure, the change of temperature profiles along the bed height show the expanded bed height or demarkation between dense and dilute phases in bubbling fluidized bed. As would be expected that the temperature profiles are very uniform along the bed height in bubbling dense bed as well as in the circulating fluidized beds. The variation of bed temperature did not produce any appreciable affect on the temperature profiles along the bed height in both bubbling and circulating fluidized beds.

The mechanism of combustion of coal in an inert fluidized bed of ash has been known that[11] combus-

Table 2. Experimental Conditions

Operating Variables of the Combustor			
Bed Temperature, °C		750, 800, 850, 900	
Air Velocity, cm/s		30-137	
Excess air factor		1.0-1.45	
Size Distribution of the Coal			
0.6-0.89 mm		0.89-1.17 mm	
d_p, mm	X_d, %	d_p, mm	X_d, %
0.601-0.673	27.71	0.894-0.970	13.05
0.673-0.794	36.69	0.970-1.016	15.88
0.794-0.894	36.60	1.016-1.171	71.87
$\bar{d}_p$ = 0.73 mm		$\bar{d}_p$ = 1.03 mm	

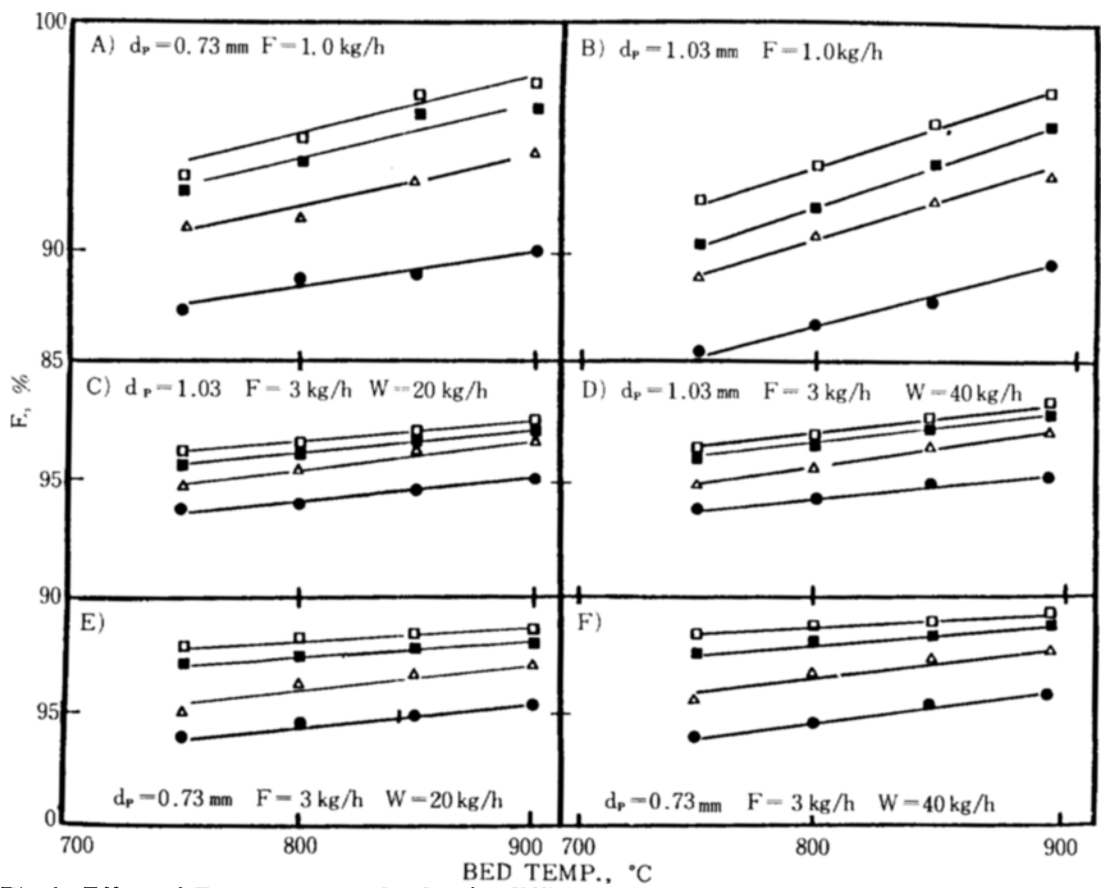

Fig. 2. Effect of Temperature on Combustion Efficiency

A, B) : V_g (cm/s), (excess air ratio) ; ● 30 (1.0) △ 35 (1.15) ■ 39 (1.3) □ 44 (1.45)

C-F) : V_g (cm/s), (excess air ratio) ; ● 90 (1.0), △ 104 (1.15) ■ 117 (1.3) □ 137 (1.45)

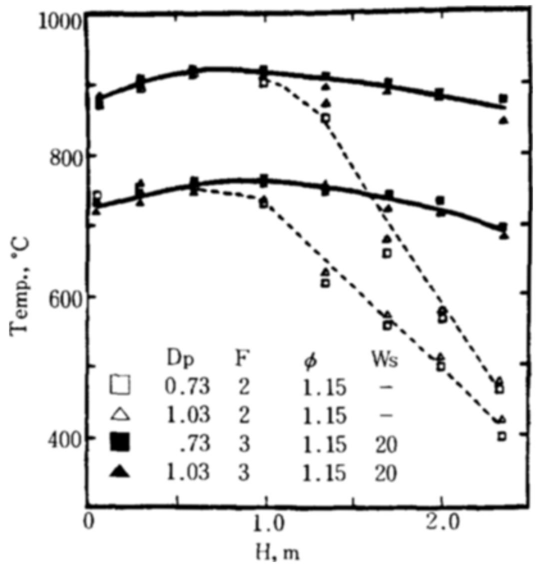

Fig. 3. Temperature Profiles in Bubbling and Circulating Fluidized Beds

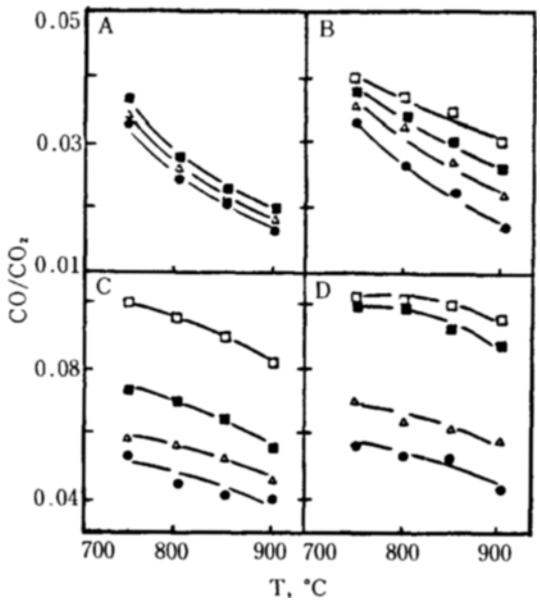

Fig. 4. Effect of Bed Temperature on the ratio of CO/CO_2 in flue gas

	d_P (mm)	F (kg/h)	W_S (kg/h)
A)	0.73	1 0	0.0
B)	1.03	1.0	0.0
C)	0.73	3.0	20.0
D)	1.03	3.0	20.0

	□	■	△	●
Excess air ratio:	1.0	1.15	1.30	1.45

tion is controlled by the interchange of oxygen from the bubble to paticle phases, and the diffusion of oxygen through the inert phase to the burning particle. The possible modes of combustion of carbon at different temperature and air velocity have been described[12] as $C + O_2 \rightarrow CO_2$ and $C + \frac{1}{2}O_2 \rightarrow CO$ which are take place at the carbon surface at low velocity and temperature range of 900-1200°C. In general, a fluidized bed coal-fired furnace operates between 800-900°C. Therefore, direct reaction of carbon with oxygen producing CO_2 and CO at the surface can be assumed for the present systems. It can be seen from Figure 4 that the ratio of CO/CO_2 in flue gas decreased with increase of

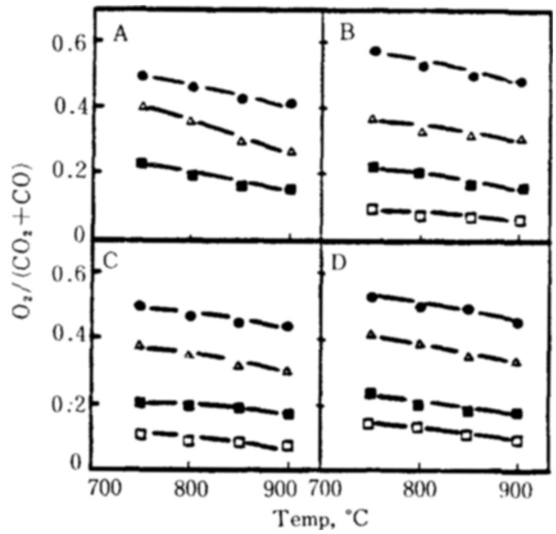

Fig. 5. Effect of Bed Temperature on the ratio of $O_2/(CO_2+CO)$

	d_P (mm)	F (kg/h)	W_S (kg/h)
A)	0.73	1.0	0.0
B)	1.03	1.0	0.0
C)	0.73	3.0	20.0
D)	1.03	3.0	20.0

	□	■	△	●
Excess air ratio :	1.0	1.15	1.30	1.45

bed temperature in bubbling and circulating fluidized beds since the reaction rate between coal and oxygen producing CO_2 increases with bed temperature. Also, carbon monoxide being yield at the carbon surface may be easily converted to CO_2 with increasing bed temperature[11]. The ratio of $O_2/(CO_2+CO)$ may indicate the rate of oxygen consumption to the production of CO and CO_2. As can be seen in Figure 5, the ratio decreased with bed temperature and it increased with the excess air ratio as expected.

Effect of Excess Air Ratio

The effect of air flow rate or excess air ratio on combustion efficiency in bubbling and circulating fluidized beds is illustrated in Figure 6. The combustion efficiency increased with increase of excess air ratio in both bubbling and circulating fluidized beds since the oxidation reaction had been enhanced by the addition of oxygen[5] in both systems. Also the exchange of oxygen from bubble to emulsion phases increases with increasing gas flow rate[6] which provides higher expanded bed height. In addition, contacting between solids and gas may increase with increasing gas flow rate due to the vigorous mixing in bubbling and circulating fluidized beds [7,8]. The rate of increase in combustion efficiency at the higher gas flow rate somewhat reduced with gas velocity since the exchange rate of oxygen to emulsion phase can be reduced with increase of bubble size. The operating bed temperature did not vary with the excess air ratio in both bubbling and circulating fluidized beds since the bed temperature was controlled with the water flow rate through the cooling tube. The ratio of CO/CO_2 decreased with the excess air ratio as shown in Figure 4. It may be due to the decrease of diffusional resistance for oxygen to reach the carbon surface with the increase of excess air ratio. Also, the ratio of $O_2/(CO_2+CO)$ increased with the excess air ratio as expected.

Effect of Particle size

With the two different particle sizes in this study, the combustion efficiency in the bed of smaller particles is somewhat higher than that of larger particle bed in bubbling and circulating flow systems. It can be attributed to the longer burning time for the larger particle size[9] and the increase of the diffusional resistance of oxygen to reach the carbon surface with the increase of particle size[10]. Also the contacting between gas and solids would be higher in the beds of smaller particles at the given gas velocity (Figure 2). The ratio of CO/CO_2 increased slightly with increase of particle size in the present systems.

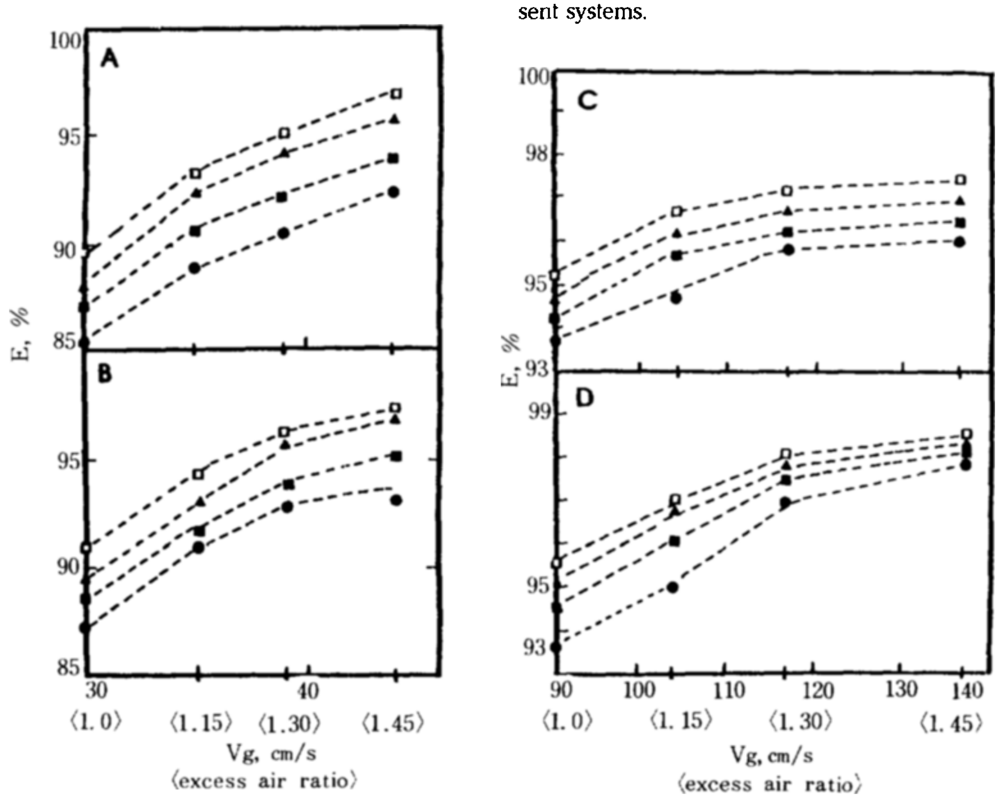

Fig. 6. Effect of Excess Air Ratio on Combustion Efficiency

	d_P (mm)	F (kg/h)	W_S (kg/h)
A)	1.03	1.0	0.0
B)	0.73	1.0	0.0
C)	1.03	3.0	20.0
D)	0.73	3.0	20.0

	●	■	▲	□
Temperature (°C) :	750	800	850	900

Effect of Recycle rate

In the circulating fluidizing bed, the unburned carbon particles can be recycled by means of the auxiliary bed in the recycle rates of 20-40 kg/h. In the present range of recycle rate, combustion efficiency increased with the increase of recycle flow rate since the residence time of fuel particles in the bed can be increased with recycle rate. In addition, the contacting between gas and solids increases with bed density with the higher recycle rate[7,8].

Correlation of Combustion Efficiency

Least square multiple regression analysis of the combustion efficiency data in bubbling fluidized bed yielded the following correlation:

$$E = 18.33T^{0.23}\phi^{0.23}F^{0.02}d_P^{-0.03} \quad (2)$$

with the correlation coefficient of 0.95.

In circulating fluidized beds, the combustion efficiency data has been correlated with the experimental variables as

$$E = 47.40\,T^{0.09}\phi^{0.12}F^{0.03}d_P^{-0.03}W_s^{0.01} \quad (3)$$

with the correlation coefficient of 0.96.

In summary, combustion efficiency increases with bed temperature and excess air ratio and it decreases with increasing particle size in both bubbling and circulating fluidized beds. Combustion efficiency in circulating fluidized bed is found to be higher than that in bubbling beds. The ratio of CO/CO_2 in the flue gas composition decreases with increasing bed temperature and excess air ratio.

NOMENCLATURE

A: ash content in the coal, %
a: ash content in the refused coal, %
d_p: particle diameter, mm
E: combustion efficiency, %
F: coal feed rate, kg/h
T: bed temperature, °C
V_g: air flow rate, cm/s
W_s: recycle flow rate, kg/h
x_d: particle size fraction, %
ϕ: excess air ratio

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