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COAL COMBUSTION CHARACTERISTICS IN A FLUIDIZED BED COMBUSTOR WITH A DRAFT TUBE

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Abstract—The effects of gas velocity to draft tube (3-6 U_{mf}), bed temperature (800-900°C) and excess air ratio (0-30%) on the total entrainment rate, overall combustion efficiency and heat transfer coefficient have been determined in an internally circulating fluidized bed combustor with a draft tube. The total entrainment rate increases with an increase in gas velocity to draft tube, but decreases with increasing bed temperature and excess air ratio. The overall combustion efficiency increases with increasing excess air ratio, but decreases with increasing gas velocity to draft tube. The overall combustion efficiency obtained in internally circulating fluidized beds was found to be somewhat higher than that in a bubbling fluidized bed combustor.

INTRODUCTION

Recently, circulating fluidized beds have been employed widely in the field of petroleum refining, coal combustion and gasification processes. The conventional circulating fluidized beds require a very tall main vessel as a solids riser and an accompanying tall cyclone. To reduce the height of the conventional circulating fluidized bed and its construction cost, several new types of circulating fluidized bed using a central draft tube [1, 2] or flat plates [3, 4] to divide the bed for internal solids circulation in a single vessel have been developed. For a combustor, it is required to operate the combustor with a wide range of load which can be controlled by the solids circulation rate. Therefore, solids circulation rate and combustion characteristics have to be determined to provide prerequisite knowledge to designing an internally circulating fluidized bed combustor.

In the present study, the effects of gas velocity to draft tube, bed temperature and excess air ratio on total entrainment rate, overall combustion efficiency and heat transfer coefficient have been determined in an internally circulating fluidized bed combustor with a draft tube. Also the results obtained are compared with those in a bubbling fluidized bed combustor and an internally circulating fluidized bed combustor with a flat plate.

EXPERIMENTAL

Experiments were carried out in an internally circulating cold model fluidized bed (0.3m-I.D.×0.6m-high) with a draft tube (0.1m-I.D.×0.3m-high) to determine solids circulation rate and in a combustor having same dimensions of the cold model bed for the combustion studies. The experimental apparatus is shown in Fig. 1. In the cold model test, hot sand (250°C) particles identical to the bed material were used as a tracer particle for measuring the downward particle velocity in the annulus by using two thermistor probes mounted on the annulus. The downward particle velocity at the center of the annulus was assumed as the average bulk velocity in the annulus [4]. The solids circulation rate was determined from the following relation:

$$W_a = \rho_s(1-\varepsilon_{mf})V_a \qquad (1)$$

The properties of sand particle used in the experiment is shown in Table 1. The gap height between the distributor plate and the bottom of draft tube plays an important role to control the solids circulation rate in the internally circulating fluidized beds. To find a suitable gap height (Hg) in the cold bed test, W_a was measured with variation of gap height from 0.065 to 0.14m [5]. The main fluidized bed combustor was constructed from a stainless steel pipe and outside

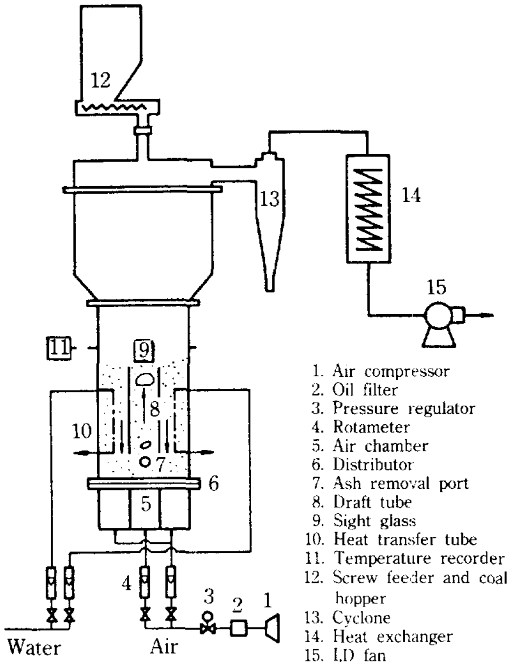

Fig. 1. Schematic diagram of experimental apparatus of a combustor.

Table 1. The physical properties of sand particle

Particle size distribution	0.25-0.46 mm
Mean particle diameter	0.311 mm
Particle density	2620 kg/m^3
Minimum fluidizing gas velocity	0.121 m/s
Bed voidage at minimum fluidizing condition	0.48

wall of the combustor was insulated by Kaowool. The combustor consisted of four parts; coal feeding, main bed combustor with two sight glasses mounted at 0.45 m above the distributor, freeboard above the combustor, and a cyclone. Coal was supplied into the draft tube from a screw feeder mounted on the freeboard and the feeding rate was regulated by using a D.C motor controller. The combustor was heated initially by using an electric heater to ignition temperature of coal (≃550℃). When the bed temperature reached 550-600℃, coal was started to feed through the screw feeder into the combustor with air supply to the draft tube and annulus through distributor and then the electric heater was cut-off. To measure the axial temperature in the annulus (moving bed) and the draft tube the combustor was mounted with 4 K-type thermocouple at 0.1m height interval from 0.05m above

Table 2. Properties of Chinchun coal

Proximate analysis(wt%)				Ultimate analysis(wt%)	
Air dry basis				C : 71.4	H : 1.2
Moisture	3.7			O : 7.7	N : 1.4
Ash	17.0			S : 1.3	
Volatile	8.5			Ash : 17.0	
Fixed carbon	70.8				
Major constituents in ash(wt%)					
SiO_2	46.2	Al_2O_3	30.8	CaO	4.8
Fe_2O_3	6.7	K_2O	1.5	MgO	1.0
MnO	0.1	Na_2O	1.0	P_2O_5	0.5
TiO_2	1.2				
High heating value		6532 kcal/kg			

Table 3. Size distribution of the coal particles

Sieve aperture μm	Size d_{pi}(μm)	Weight fraction x_i
6,730-4,000	5,365	0.285
4,000-2,380	3,190	0.208
2,380-1,680	2,030	0.122
1,680-1,410	1,545	0.033
1,410-1,000	1,205	0.113
1,000-710	855	0.107
710-500	605	0.056
500-420	460	0.023
420-350	385	0.023
350-250	300	0.030

$d_p = \Sigma \frac{1}{x_i/dp_i} = 1.387$ mm

the distributor and 2 K-type thermocouple at 0.2m height interval from the bottom of draft tube, respectively. A vertical heat transfer tube (7.7 mm-I.D×0.2m length) was mounted at 0.1m from the distributor within the moving bed to determine the heat transfer coefficient. When the combustor reaches steady state operation, water was introduced into the heat transfer tube and the temperatures of cooling water were measured at inlet and outlet of the heat transfer tube. A cyclone (0.16m-I.D×0.64m-high) was installed at the outlet of combustor. The weight of ash collected in cyclone was measured with time. The fraction of unburned carbon was determined from the complete burn-off of flyash in a furnace. The proximate and ultimate analyses of the coal are shown in Table 2. The size distribution of the coal particle is shown in Table 3.

The overall heat transfer coefficient is given by [6]

$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{x_w A_o}{k_w A_m} + \frac{A_o}{A_i}\frac{1}{h_i} \qquad (2)$$

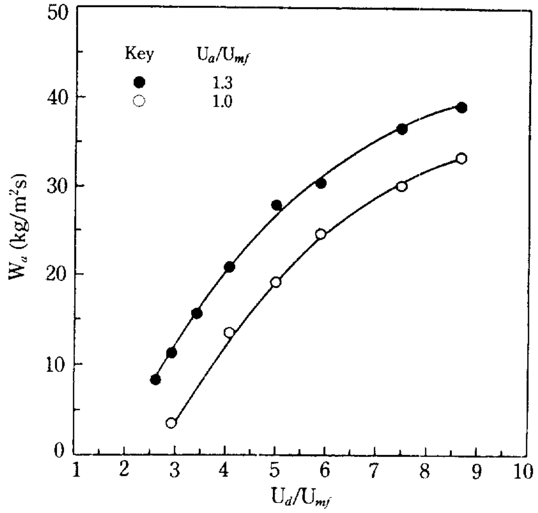

Fig. 2. Effect of gas velocity to draft tube on solids circulation rate at 0.09m gap height and different U_a/U_{mf}.

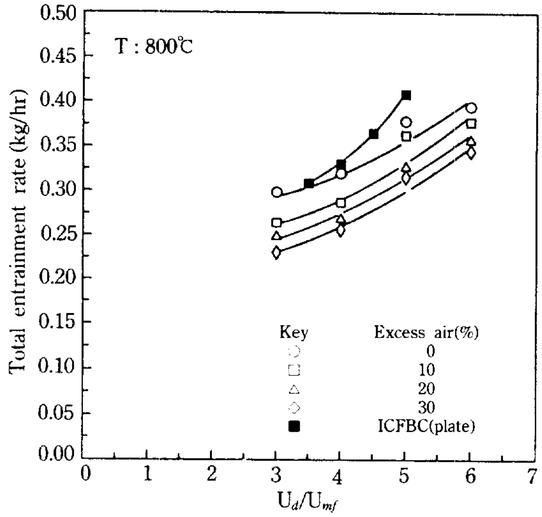

Fig. 3. Effect of gas velocity to the draft tube on total entrainment rate.

From the energy balance between the bed and the cooling water, the overall heat transfer coefficient in the bed has been determined from the following relation

$$U_o = \frac{m_w C_{pw} (T_{wo} - T_{wi})}{A_o \Delta T_{lm}} \tag{3}$$

The heat transfer coefficient for inside of the heat transfer tube (h_i) can be calculated from the following equation [7].

$$\frac{h_i D_i}{k_w} = 1.75\left[\frac{m_w C_{pw}}{k_w L}\right]^{1/3} \tag{4}$$

Thus, the heat transfer coefficient for outside of the heat transfer tube (h_o) has been determined from Eqs. (2), (3) and (4).

RESULTS AND DISCUSSION

The effect of gas velocity to draft tube (U_d) on solids circulation rate (W_a) at different U_a/U_{mf} at gap height of 0.09m is shown in Fig. 2. As can be seen, W_a increases with increasing U_d due to the increase of driving force between the two beds with increasing bed voidage difference in the draft tube and the annulus [1]. However, the rate of increasing in W_a decreases due to the solids back mixing at the base of draft tube and the loss of dense phase solid clusters in the annulus with increasing jet diameter with U_d [8]. Also as the gas velocity to draft tube increases gas bypassing from the annulus to the draft tube increases and solids flow from annulus to draft tube improves by cocurrent gas flow. Solids circulation rate at higher U_a/U_{mf} was shown to larger than that at lower U_a/U_{mf} due to decreasing the stagnant zone formed at annulus base.

Based on the cold bed test, the combustion experiment was carried out at the following experimental conditions as: $U_a/U_{mf}=1.3$, the distance between the draft tube inlet and the distributor was 0.09m and the static bed height was fixed at 0.35m.

The effect of U_d on the total entrainment rate at different excess air ratios is shown in Fig. 3. The total entrainment rate increases with increasing U_d due to the increase in the entrainment from coal feeding, the particle entrainment by bubble rupture at the bed surface, the entrainment from the particle attrition and the drag force acting on the particles within the freeboard [9-11]. Also the total entrainment rate decreases with an increase in excess air ratio due to decrease in the entrainment from the bed by decreasing the carbon concentration in the bed and the carbon content in coal particle with increasing reactivity of coal particles with the excess air in the bed and freeboard sections. As can be seen in Fig. 3, the total entrainment rate is smaller than that of Park et al. [15] in an internally circulating fluidized bed combustor with a flat plate.

The effect of bed temperature on total entrainment rate at a given gas velocity (5 U_{mf}) and an excess air ratio (20%) is shown in Fig. 4. As can be seen, the total entrainment rate decreases with increasing bed temperature due to the increase in reactivity of carbon

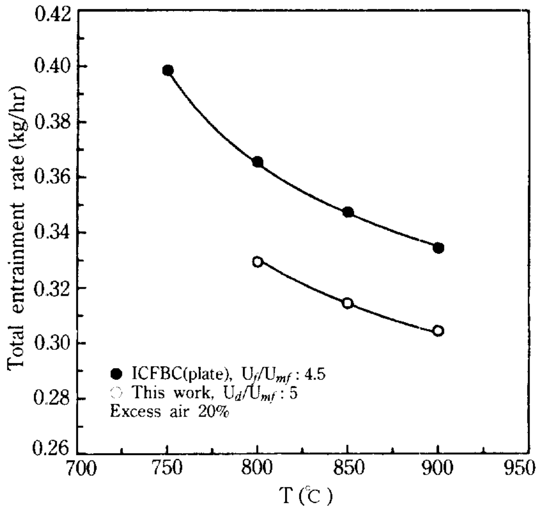

Fig. 4. Effect of bed temperature on total entrainment rate.

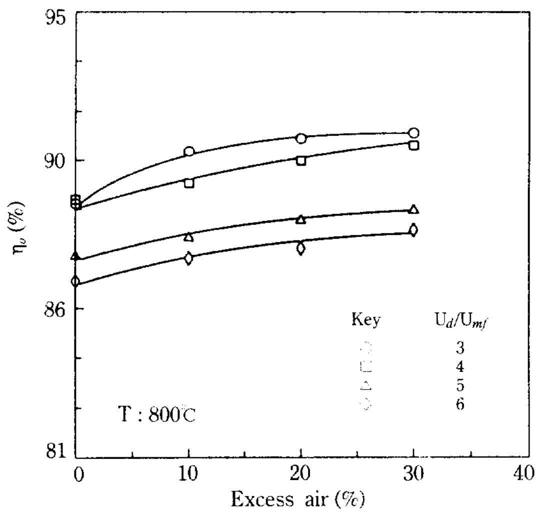

Fig. 5. Effect of excess air ratio on the overall combustion efficiency.

in the bed, recombustion of entrained particle in the freeboard and a decrease in gas density with increasing bed temperature [11].

The overall combustion efficiency (η_o) can be defined as:

$$\eta_o = 1 - W_{uc}/W_t \quad (5)$$

where W_{uc} is the amount of unburned carbon in flyash and W_t is the amount of carbon in coal feeding.

The effect of excess air ratio on η_o at different U_d is shown in Fig. 5, where η_o increases with increasing

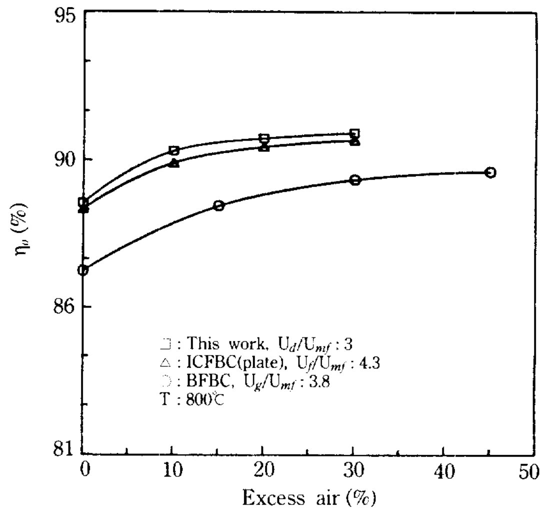

Fig. 6. Comparison of overall combustion efficiency between the internally CFB and conventional FBC at temperature of 800°C.

excess air ratio and decreases with increasing U_d. This may be attributed to the increase in the reactivity between C and O_2 due to an increase in O_2 concentration [13] and the gas-solid contact efficiency may increase due to the increase of mass transfer rate of oxygen from bubble phase to emulsion phase with increasing excess air ratio [14]. However, η_o decreases with U_d due to the loss of unburned carbon by increasing of total entrainment rate with U_d.

The overall combustion efficiencies of the present and previous studies in a bubbling fluidized bed [16] and an internally fluidized bed combustor with a flat plate [15] are shown in Fig. 6. As can be seen, η_o in the internally circulating fluidized beds exhibits larger η_o than that in a bubbling bed [16] since the former beds have longer residence time of coal particles by induced solids circulation within the bed.

The effect of gas velocity to draft tube (U_d) on η_o is shown in Fig. 7 in which η_o decreases with increasing U_d due to the increase of unburned carbon loss by increasing entrainment rate with U_d. Therefore, it is desirable that a combustor used in present study is operated at the optimum operating conditions for the increase of fuel loading and the decrease of overall combustion efficiency with increasing gas velocity.

The heat transfer coefficients (h_w) between a vertical heat transfer tube in the moving and the fluidized beds [15] are shown in Fig. 8. As can be seen, h_w in the moving bed increases with increasing U_d and bed temperature since particle residence time on the heat transfer tube surface decreases with increasing

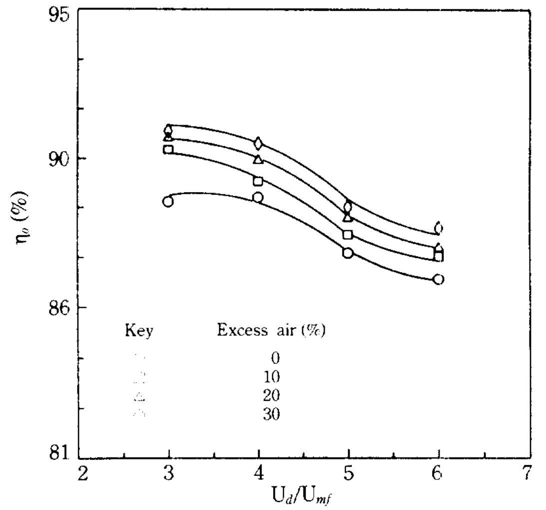

Fig. 7. Effect of gas velocity to the draft tube on the overall combustion efficiency.

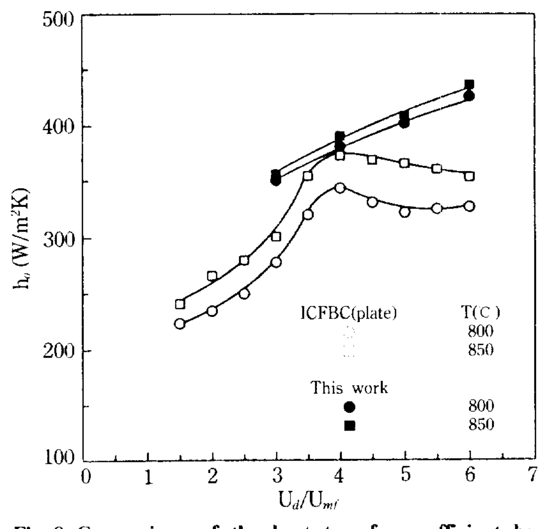

Fig. 8. Comparison of the heat transfer coefficient between the fluidized and moving beds.

W_a and consequent increase in net heat flux [17]. Also, h_o increases with bed temperature due to the increase in specific heat of solids which increases with the 0.5 to 1.0 power of specific heat of solids [18]. Heat transfer in a fluidized bed is mainly governed by heat conduction and convection but it may be controlled by conduction in the moving bed [19]. Heat may be primarily transferred from the bulk of solids in the bed by convection, and the convective heat transfer through the gas is relatively small. The typical heat transfer coefficient in the bed of horizontal flow of solids are reported to be in the range of 227-567 W/m^{2}K [20]. In a moving bed with relatively small particle movement, the thermal conductivity of solids is the controlling factor to govern the heat transfer. As can be seen, h_o in the moving bed is larger than that in the fluidized bed at a given U_d since bed voidage is smaller in the moving bed with high heat capacity of solid for solids conduction [15].

Correlation

Solids circulation rate in the cold model fluidized bed with a draft tube in the present study has been correlated with the pertinent dimensionless groups as

$$\frac{W_a}{\rho_s(1-\varepsilon_{mf})U_{mf}} = 4.67\times10^{-3}\left[\frac{U_d U_a}{U_{mf}^2}\right]^{1.74}[1-(Hg/H)]^{-0.91} \quad (6)$$

with a correlation coefficient of 0.94 with the range of variables $2.67<(U_dU_a/U_{mf}^2)<8.0$ and $0.533<(1-Hg/H)<0.783$.

CONCLUSIONS

The solids circulation rate increases with increasing gas velocity to draft tube. The total entrainment rate increases with increasing gas velocity to draft tube but, decreases with an increase in bed temperature and excess air ratio. The overall combustion efficiency increases with increasing excess air ratio, but decreases with increasing gas velocity to draft tube. The overall combustion efficiency in internally circulating fluidized beds is larger than that in bubbling bed. The heat transfer coefficient in the annulus increases with increasing gas velocity to draft tube and bed temperature.

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NOMENCLATURE

- A_i : internal area of heat transfer tube [m^2]
- A_m : logarithmic mean area of heat transfer tube [m^2]
- A_o : external area of heat transfer tube [m^2]
- C_{pw} : specific heat of water [J/kg·K]
- D_t : inside diameter of heat transfer tube [m]
- H : height of draft tube [m]
- Hg : distance of draft tube inlet and distributor [m]
- h_i : inside individual heat transfer coefficient [W

/m²K]

h_o : outside individual heat transfer coefficient [W/m²K]

k_w : thermal conductivity of water [W/mK]

L : length of heat transfer tube [m]

m_w : water flow rate in heat transfer tube [kg/s]

ΔT_{lm} : logarithmic mean temperature between bed and heat transfer tube [K]

T_{wi} : inlet temperature in heat transfer tube [K]

T_{wo} : outlet temperature in heat transfer tube [K]

U_a : superficial gas velocity to the annulus [m/s]

U_d : superficial gas velocity to the draft tube [m/s]

U_f : gas velocity in the fluidized bed [m/s]

U_{mf} : minimum fluidizing gas velocity [m/s]

V_a : bulk particle velocity in the annulus [m/s]

W_a : solids circulation rate per unit area of annulus [kg/m²s]

ε_{mf} : voidage at minimum fluidization conditions [-]

ρ_s : density of solid particle [kg/m³]

η_o : overall combustion efficiency [%]

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