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EFFECT OF ENTRAINMENT ON COMBUSTION EFFICIENCY (HIGH ASH ANTHRACITES IN FLUIDIZED BED COMBUSTORS

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Abstract— The characteristics of the freeboard combustion of Korean low grade anthracites were studied in two fluidized bed combustors, which employed over-bed feeding and non-recycle of cyclone captured solids. The total combustion efficiency was ruled mainly by entrainment of fed coal particles and more or less by the freeboard combustion of entrained coal particles. The conversion of entrained coal particles increased with the bed temperature and decreased with the higher coal feed rate per bed area.

1. INTRODUCTION

After oil crises many countries looked towards their domestic energy reserves to supply a larger portion of their needs. In some cases the new economic conditions made them pay attention to using their low grade domestic fuels. In Korea, the low grade anthracite which is the waste from mining operation or was formed intrinsically is now considered economical to recover and utilize as an energy resource.

Fluidized bed combustion has been well-known to be capable of burning high ash, low heating value, low volatile fuels. After earlier researches [1-4] on the composite combustion model of Korean anthracite, several studies [5-13] on combustion, heat transfer and other experiences in the fluidized bed combustion of the Korean low grade anthracite have been reported and Park et al. [14] performed the experiment and model determination in cold mode and hot combustors.

Several FBC experiences have indicated that for certain operating conditions a significant fraction of the total combustion occurred in the freeboard of the combustor. The effect would be most pronounced under conditions of high gas velocity and/or small bed particle size, when the solid concentration in the freeboard became higher. In the freeboard solid particles thrown up from the bed surface are in contact with any reactant gas emerging unconverted from the bed below. Although the freeboard lacks the thermal stability of the bed itself, it is unlikely to suffer from the frequently deleterious gas bypassing characteristics of a bubbling bed, and as a result of this enchanced gas-solid contact, it is likely that reactions will go further towards completion in this region.

As the particles are entrained by the bubbles and gas stream over the bed surface, some particles with terminal velocities greater than the superficial gas velocity (coarse or large particles) will reach a certain height within freeboard, however, others which have terminal velocities smaller than the superficial gas velocity (fine or small particles) will, eventually, be carried out of the bed or elutriated. During the solid-gas disengagement process, additional particles may also fall down if they hit the wall. Therefore the movement of solids in freeboard is attributed to the gas flow pattern, which, consequently, determines the particle loading and its residence time in this region.

The key factors to the freeboard reaction are solid loading and its residence time in the freeboard. The freeboard reaction in a fluidized bed reactor has been shown important by several investigation [15-18]. Yates and Rowe [15] studied a model for a catalytic reaction in the freeboard on the assumption that the solid concentration profile is constant. Based on a machanistic solid entrainment model, De Lasa and Grace [16] proposed a freeboard model for the fluidized bed catalytic cracking regeneration. But it was indicated by Chen and Wen [18] that most of assumptions of early proposed models were over simplified and unrealistic. Thus Chen and Wen [18] suggested a more realistic freeboard reaction model for NO_x reduction and SO_2 absorption in FBC, with the consideration of the solid entrainment rate and the solid velocity. As to the freeboard

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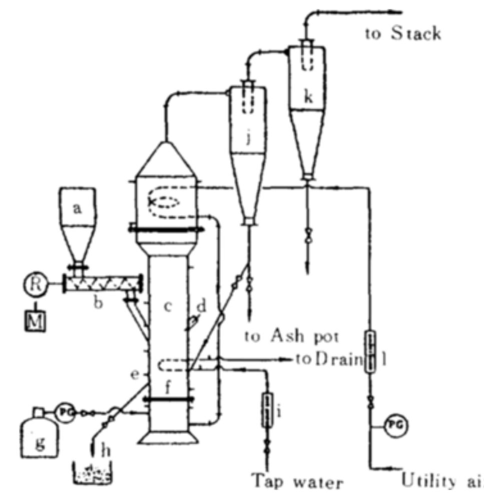
combustion in a fluidized bed coal combustor, Tung et al. [17] reported a definite model with assumptions on the initial entrainment from the bed surface by terminal particle size at the bed surface and the exponentially decayed particle loading in the freeboard.

But existing models mentioned above are insufficient yet to relate two key factors correspondingly to the freeboard phenomena and moreover, the difficulty in identifying the boundary between the bed and freeboard makes accurate assessment of freeboard combustion further impossible. Hence in order to predict the freeboard reaction adequately, a more complicate mechanic model solving such defects should be developed in the future. This study was intended to identify the effect of entrainment on combustion efficiency of Korean low grade anthracites in fluidized bed combustors and, in advance, to characterize the freeboard combustion empirically with operating variables.

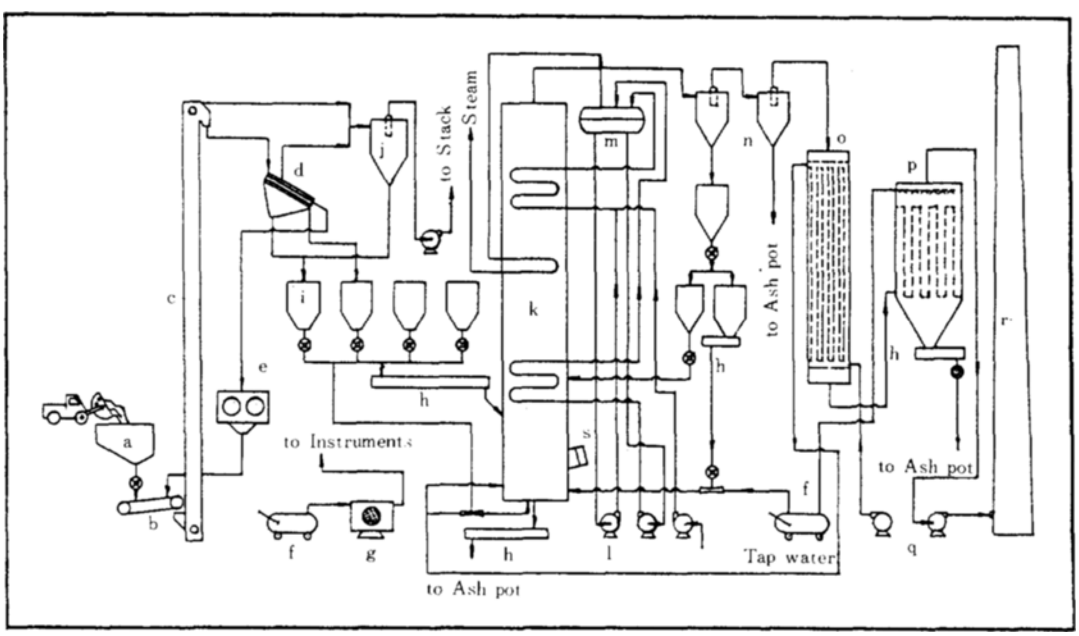
2. EXPERIMENTAL

Ealier experiments to investigate the combustion characteristics of a coal had been performed in a bench scale combustor of 0.15 m in diameter as shown in Fig. 1 which was similar in process with the pilot scale facilities in Fig. 2. The specifications of both combustors



a. Coal Hopper
b. Screw Feeder
c. Combustor
d. Peeping Hole
e. Pressure Taps and Thermocouples
f. Distributor
g. LPG Tank
h. Ash Pot
i. Water Flow Meter
j. First Cyclone
k. Second Cyclone
l. Air Flow Meter
M : Motor
PG : Pressure Gauge
R : RPM Controller

Fig. 1. Schematic diagram of the bench scale fluidized bed combustion system.



a. Coal Storage Bin
b. Conveyor
c. Elevator
d. Screen
e. Crusher
f. Compressor
g. Dryer
h. Screw Conveyor
i. Coal Bins
j. Dust Cyclone
k. Combustor
l. Pumps
m. Steam Drum
n. Cyclones
o. Air Preheater
p. Bag House
q. Fans
r. Stack
s. Start-up Burner

Fig. 2. KIER pilot plant flow diagram.

are listed in Table 1. A bench scale combustor had a circular crossection and a pilot scale combustor had a rectangular one of 0.3 m x 0.3 m in bed size. The perforated and multi-tuyere type distributors were employed respectively and in both scales over-bed feeding method by gravity, which was generally accepted in commercial application, was selected for the measurement. Coal was conveyed by a screw conveyor and dropped by gravity over the bed surface. The bed height was maintained nearly constant by draining bed material periodically, which was monitored from the differential pressure measured between in-bed and freeboard. At the start-up, bed materials were preheated directly by burning LPG injected with fluidizing air. Two sets of horizontal in-bed heat exchanger was submerged producing hot water in the bed and freeboard and in case of the bench scale unit, the freeboard heat exchanger set played a role of the air preheater. Preheated air was supplied into the bed through an air plenum and a distributor. Thermocouples and water manometers were used to measure the temperature distribution and pressure differences, respectively, along the combustor axis.

The actual ignition temperatures of tested coals were around 650°C in fluidized beds, indicating much higher values than those of laboratory tests (about 580°C) reported in [19]. Therefore the bed temperature should be raised over 700°C before switching LPG to coal gradually. Ignition of the injected coal could be recognized by a rapid increase of the bed temperature recorded on the strip chart recorder at the beginning of coal feed. After turning off start-up burner, the bed conditions, such as bed height and fluidizing velocity, were adjusted to reach an appropriate operating condition step by step.

In pilot plant tests, however, it had to be careful at the time of start-up not to allow build-up of larger particle at the bottom of the bed, resulting in defluidization. Defluidization could be detected quickly by the abnormal temperature drop, which used to be occured at the defluidizing zone and against the normally uniform temperature distribution all over the bed at the well fluidizing condition. Such local defluidization sometimes happened at the bottom of the bed and could be solved easily by removal of bed materials through the draining pipe at the bottom of the bed.

Freeboard pressure was maintained at- 20mm water in pilot scale tests and at ambient pressure in bench scale tests. Flue gas was discharged after cooled down to about 400°C in the freeboard and gas sampling for analysis was done at the exit of the combutor. Most of the elutriated fines were captured by two cyclones in series and fluidizing air was preheated over 100°C by recovered waste heat from the flue gas stream.

The air flow rate was measured by the rotameter. Operating ranges of both scales are listed in Table 2. Coal feed rates per bed area ranged from 60 to 170 Kg/hr m^2 in bench scale tests and from 550 to 900 Kg/hr m^2 in pilot scale tests. The excess air level and bed tempera-

Table 1. Combustor specifications.

specifications	bench scale	pilot scale
distributor	perforated type opening : 1.5%	multi-tuyere type opening:2%
bed	diameter: 0.15m height : 0.6m	area: 0.3×0.3m^2 height : 1.7m
freeboard	diameter: 0.25m height : 0.4m	area: 0.45×0.45m^2 height : 2.5m
feed point	over the bed surface	over the bed surface
bed draining exit	bottom of the bed	bottom of the bed

Table 2. Operating conditions.

items	bench scale	pilot scale
coal feed rate, Kg/m^2hr	60 – 170	550 – 900
excess air, %	0 – 50	0 – 50
bed temperature, ℃	800 – 900	700 – 950
freeboard temp., ℃	500 – 700	500 – 700
gas velocity in the bed at operating conditions, m/sec	0.3 – 0.75	1.4 – 2.2
gas velocity in the freeboard at operating conditions, m/sec	0.1 – 0.75	0.5 – 0.81
static bed height / bed diameter	0.9 – 1.5	1 – 3

Table 3. Coal properties.

items	bench scale	pilot scale	
size range, mm	0 – 2	0 – 6	
surface mean size, μm	120 – 145	360, 590	
heating value, Kcal/Kg	2800	1800, 2500	
proximate analysis of coals, (unit: fraction) :			
moisture	0.0342	0.0144	0.0535
ash	0.5865	0.7285	0.5950
volatiles	0.0319	0.0414	0.0250
carbon	0.3474	0.2157	0.3265

Table 4. Size analysis of raw coal (heating value: 2800Kcal/Kg).

screen size, (mesh)	weight fraction	cumulatives, (%)
over 4	0.038	3.8
4 - 6	0.099	13.7
6 - 8	0.096	23.3
8 - 10	0.043	27.6
10 - 14	0.086	36.2
14 - 20	0.132	49.4
20 - 30	0.089	58.3
30 - 40	0.063	64.6
40 - 60	0.084	73.0
60 - 80	0.139	86.9
80 - 100	0.058	92.7
100 - 140	0.043	97.0
140 - 170	0.004	97.4
170 - 200	0.010	98.4
under 200	0.016	100.0

Surface mean diameter, D_{ps}=0.391mm

ture were varied from 0 to 50 percentage and 700 to 950 degree of centigrade respectively so as to examine each effect.

The properties of coals employed are shown in Table 3. Coal sizes were prepared under 2mm in bench scale tests and under 6mm in pilot scale tests. A typical size distribution of Coal, which was employed in pilot scale tests, is shown in Table 4 and as indicated, fine particles under 60 ASTM mesh, 250 μm, are up to 27 percentage.

3. RESULT AND DISCUSSION

Generally the factors that influence the combustion efficiency were known as (1) loss of carbon in the elutriated solids, (2) loss of carbon in the bed drain and (3) loss of carbon as CO due to incomplete combustion. In this test the combustion efficiency was calculated by carbon balance considering all the factor mentioned above. However, through widely operating conditions, CO concentrations in flue gas were hundreds ppm and heat losses due to CO were negligible. Therefore the carbon loss nearly depends on the amount of discharged solids and their carbon concentration.

3-1. Solid discharge and carbon concentration

Typical size distribution of coal employed in pilot scale tests, its bed ash and fines collected in the first

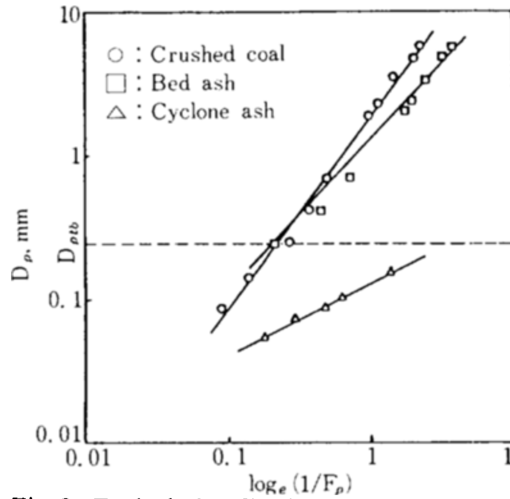


Fig. 3. Typical size distribution of a coal (heating value: 1800Kcal/Kg) and its ashes. T_{bed} : 920℃, U_{bed} : 2.13m/sec

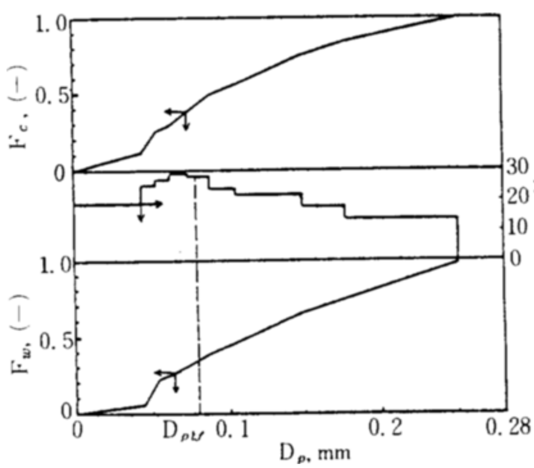


Fig. 4. Size and carbon distribution of solids captured by the first cyclone.
T_{bed} : 920℃, T_{fr} : 545℃, U_{bed} : 2.13m/s, U_{fr} : 0.649m/s

cyclone are shown in Fig. 3. The maximum size of cyclone-captured solids was similar with the terminal particle size on the bed surface, D_{ptb}, 255 μm. The amount under D_{ptb} in the bed-drained solids was much small, indicating that most of the smaller particles than D_{ptb} were elutriated from the bed section and eventually moved out of the combustor immediately or after further size reduction by means of attrition and combustion in the freeboard.

Fig. 4 showes the size distribution of solids collected in the first cyclone and its carbon distribution. Most solids were under terminal particle size of the bed section, as discussed in the Fig. 3 and their carbon content were between 14 and 29 weight percentage. In addition it showes the maximum carbon content at 68 μm in mean size. From these it could be inferred that the carbon content of elutriated solid was affected by both the burn-out time and the residence time in the freeboard. The larger particles (but$<D_{ptb}$) spend comparatively long time in the freeboard under continuous size reduction and as particle size is reduced, freeboard residence time decreases because of an increase in drag force as compared to particle weight. The smaller particles, which are capable of being elutriated sufficiently from the freeboard also, have progressively shorter residence time but because of the shorter burn-out time the carbon content becomes smaller. Therefore at some particle size around D_{ptf}, 80.9 μm of which the freeboard superficial gas velocity equals to terminal velocity, the maximum carbon content will appear as shown in Fig. 4

On the other hand, over the whole operating range carbon concentrations in the bed-drained ash indicated minor dependency on the bed temperature as well as values under 1 weight percentage, as generally reported.

3-2. Combustion efficiency

In previous bench scale combustion tests combustion efficiency was seriously affected by fluidizing gas velocity, size distribution of coal, coal feed rate per bed area and bed temperature. Consequently these results were considered to be derived from the entrainment of unburned carbon out of the bed section and from the extent of the freeboard combustion of entrained solids, as inferred by Fig. 4. Fig. 5 shows the increasing effect of coal size on combustion efficiency in the given operating range. The smaller coal size was, the greater entrained portion of feeding coal was with less combustion and hence the combustion efficiency was diminished. The effect of bed temperature is illustrated in Fig. 6. The combustion efficiency increased with the bed temperature, which was due to the further extent of freeboard combustion of entrained soilds, considering that the loss of carbon in the bed drain indicated negligible dependency on the bed temperature. The freeboard combustion will be further discussed later in detail. On the other hand combustion efficiency showed minor dependencies on the bed height and excess air level, as similar with (20), which was in contrast to the other experimental results reported in the literature which showed an increase in overall combustion efficiency with them. Thus for an adequate determination of their effects further available data should be required.

3-3. Freeboard combustion

The combustion in the fluidized bed combustor can be divided into the bed and freeboard combustion. In AFBC the carbon loss is mostly attributed to the elutriation of solid carbon from the bed because the carbon loss through the bed-drained material is usually small as

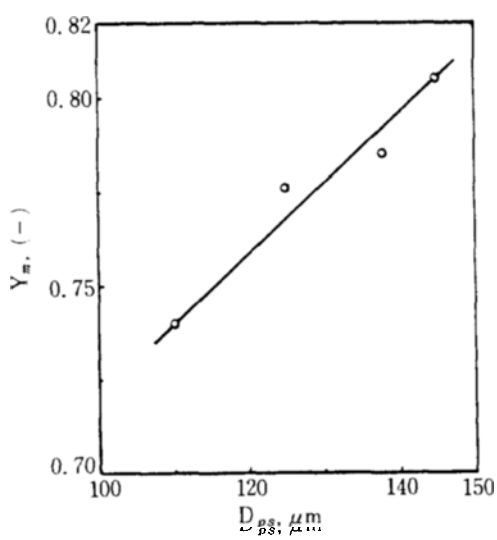


Fig. 5. Effect of coal size on combustion efficiency in bench scale tests.
X : 35%
T_{bed} : 800℃
U_{bed} : 45.3cm/sec
F/A_{bed} : 100kg/m² hr

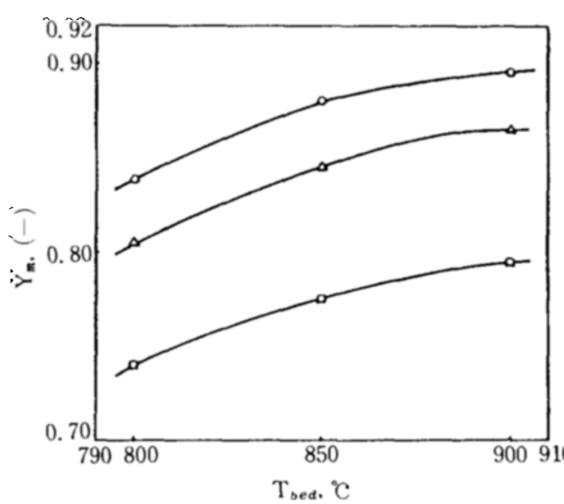


Fig. 6. Effect of bed temperature on combustion efficiency in bench scale tests.
D_{ps} : 145 μm X : 35%

U_{bed}, cm/sec	F/A_{bed}, Kg/m²hr
○ : 32.6	68.5
△ : 44.5	93.4
□ : 71.0	149.0

discussed above. This is due to the fact that the elutriable carbon solid generally has the shorter residence time in the combustor, while the bed solid has hours of residence time. Therefore, since the bed solid can be regraded as burning completedly, the combustion efficiency may be affected more or less by the freeboard combustion of entrained particles.

The freeboard combustion was reported to depend on solid loading by entrainment and the residence time in the freeboard. The particles entrained by bubbles and the gas stream will either rise or fall in the freeboard, depending on the size and density of the particles and the gas velocity. However, based on the fact that most of the entrained solids are concentrated very near the surface of the bed, it is difficult to identify the exact bed surface and quite limited to assess the accurate freeboard combustion. Thus, as examining the behaviour of solid movement and experimental results such as Fig. 3 and 4, now the criteria are set up to determine the amount of freeboard combustion, which are similar with ones of Tung et al. [17].

The traveling path of the fed coal particles in the over-bed feeding system can be pictured as the following three patterns:

1) coal particles, which are small enough to reach the terminal velocity at the local conditions of the expanded freeboard region, will be flied out of the combustor immediately after feeding,

2) coal particles, which are larger than the above case but small enough to reach the terminal velocity at the local conditions of the bed, will be circulated at beginning somewhere around the freeboard. However, they will experience size reduction by the result of combustion and attrition during the motion in that region and eventually will be discharged out of the combustor,

3) coal particles, which are dropped in the bed, are to be shrinked in size by combustion and attrition taking place within the bed, which will result in the elutriation of the formed fines from the bed and finally will be drained by bed drain.

Thus if carbon content in bed drain is neglected within the error range which will be admitted in sampling and analyzing, the carbon loss in the combustor could be expected mainly by two factors. One was entrainment of original fines in the feed coal and another was elutriation of formed fines from the bed, however, the latter had been reported negligible by [21].

Total combustion efficiency consists of bed and freeboard combustion efficiencies of fed coal.

$$Y = Y_{cb} + Y_{cf} \quad (1)$$

and then the bed combustion efficiency, Y_{cd} can be decided by the evaluation of terminal particle size, D_{ptb} on the bed surface and by the size distribution of coal,

$$Y_{cb} = 1 - E_{pd}/F \quad (2)$$

where F is the coal feed rate, and E_{pb} is the entrained quantity in fed coal, which is determined theoretically by the coal size distribution and D_{ptb}. Accordingly, the freeboard combustion, Y_{cf}, from measured combustion efficiency, Y_m, is related,

$$Y_{cf} = Y_m - Y_{cb} \quad (3)$$

and for convenience, a parameter, Y_{pd} which represents the mean conversion of entrained solids within the freeboard region, is defined as follows.

$$Y_{pd} = Y_{cf}/(1 - Y_{cb}) \quad (4)$$

Fig. 7 showed the effect of coal feed rate on the extent of freeboard combustion, Y_{pd}, with the bed temperature as a parameter, obtained from bench scale tests. Under a given operating conditions, Y_{pd} decreased with coal feed rate and it could be predicted that increase of coal feed rate produced the larger flux of entrained solids into the freeboard of given solid loading, which incurred the shorter retention time of them in the freeboard. Re-

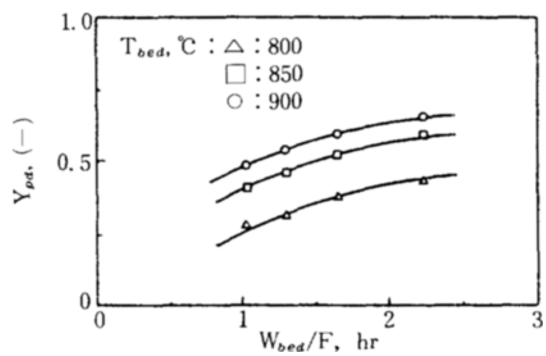


Fig. 7. Effects of bed temperature and coal feed rate on the combusted portion of entrained particles within the freeboard.

D_{ps} : 145μm, X : 35%, H_s : 0.14m

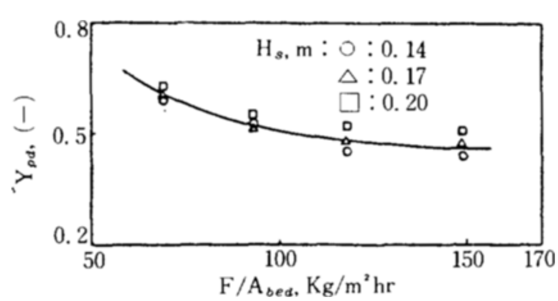


Fig. 8. Effect of bed height on the combusted portion of entrained particles within the freeboard.

T_{bed} : 850℃, D_{ps} : 145μm, X : 35%

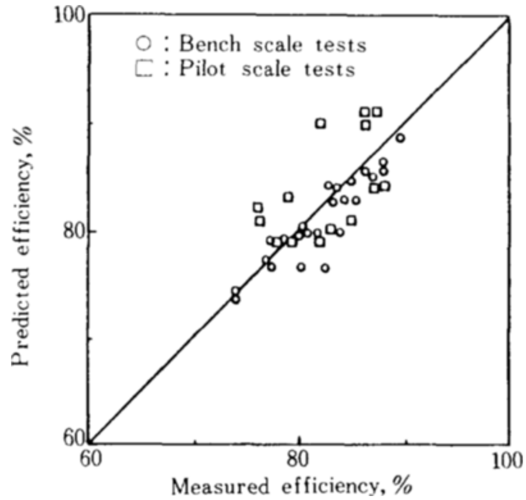


Fig. 9. Comparison of predicted efficiencies with measured efficiencies from bench and pilot scale tests.

sultantly the conversion of them became decreased. The extent of freeboard combustion, Y_{pd} increased with bed temperature due to the faster combustion rate, as could be expected. On the other hand Y_{pd} appeared minorly dependent on the fluidizing velocity, as reported by [20] and the effect of static bed height on Y_{pd} could be neglected within the operating range concerned, as seen in Fig. 8. As a result of bench scale tests, following regression equation was obtained to show Y_{pd} as a function of coal feed rate per bed area, F/A_{bed}, Kg/hr m^2, and bed temperature, T_{bed}, °C,

$$Y_{pd} = -0.1944 + 0.001853\ T_{bed} - 0.20\ \ln (F/A_{bed}) \quad (5)$$

where the regression coefficient is 0.954. Finally the combustion efficiency, Y can be calculated by Eq(1), (2), (4) and (5).

$$Y = Y_{cb} + Y_{pd}(1 - Y_{cb}) \quad (6)$$

Fig. 9 showes the comparison of predicted combustion efficiencies and measured ones in pilot scale tests, which were performed at the conditions of Table 2. Measured and predicted efficiencies showes good agreement within 7% error and that two different scales of combustors tested have similar combustion characteristics. However care should be taken for Eq. (5) to be applied to other combustors because this study covered merely two testing units and low grade anthracite characterized by Table 3.

4. CONCLUSION

In the non-recycle and over-bed feed system which employed Korean low grade anthracites, the combustion efficiency was found to be controlled by the entrainment of fed coal and its freeboard combustion. The extent of freeboard combustion of entrained particles was indicated to increase with the bed temperature and decrease with the higher coal feed rate per bed area.

NOMENCLATURE

A_{bed} : bed crossectional area, (m^2)
D_p : particle size, (mm)
D_{ps} : surface mean particle size, (μm)
D_{ptb} : terminal particle size on the bed surface, (μm)
D_{ptf} : terminal particle size in the freeboard, (μm)
E_{pd} : entrainment rate of fed coal on the bed surface, calculated from D_{ptb} and the coal size distribution, (Kg/hr)
F : coal feed rate, (Kg/hr)
F_c : cumulative weight fraction of carbon, (–)
F_p : cumulative weight fraction over D_p,(–)
F_w : cumulative weight fraction under D_p, (–)
H_s : static bed heigh, (m)
T_{bed} : bed temperature, (°C)
T_{fr} : freeboard temperature, (°C)
U_{bed} : bed superficial velocity, (m/sec)
U_{fr} ; freeboard superficial velocity, (m/sec)
W_{bed} : bed weight, (Kg)
X : excess air level, (%)
X_c : carbon content, (%)
Y : combustion efficiency, (–)
Y_{cb} ; bed combustion efficiency of fed coal calculated from D_{ptb} and the coal size distribution, (–)
Y_{cf} ; freeboard combustion efficiency of fed coal, (–)
Y_m : measured combustion efficiency, (–)
Y_{pd} : combusting fraction of entrained coals within the freeboard, (–)

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