The effect of coal particle size on the performance of a fluidised bed coal combustor

by

M. Brikci-Nigassa, E.S. Garbett and A.B. Hedley

Sheffield Coal Research Unit, Department of Chemical Engineering and Fuel Technology, University of Sheffield
Sheffield S1 3JD, United Kingdom.

Introduction

The technology of fluidised bed coal combustion (FBC) and its advantages over conventional coal burning systems is now well established and is extensively reported in the literature (1,2,3,4). A common way of introducing coal to the bed is via coal feed points in the distributor plate and for this method it is usual to use crushed coal of particles less then 6 mm. Problems associated with this method include the determination of the correct number and spacing of feed points, blockages and the obvious expense in coal preparation. Crushed coal is used because it was thought necessary to keep the coal particle sizes approximately equal to those making up the bulk of bed and so maintain good fluidisation characteristics. However, Highley et al. (5) showed that large coal particles (< 50 mm) could be burnt quite easily in an FBC whilst at the same time overcoming the coal feed problems outlined above by overbed feeding. Also, using uncrushed coal allows the bed and freeboard heights to be reduced (5) making obvious savings in capital and running costs. An increase in the size of coal particle fed to the combustor results in an increase in the bed carbon loading (6) which influence such important phenomena as NO emissions and elutriation (7). However, there is little information on the effect on the performance of an FBC due to a variation of particle size in the coal feed. This paper therefore, reports a study of the combustion of monosized coal fractions fed continuously to the bed via an overbed feeder. Data showing the effect of coal size, excess air and combustion efficiency are presented. Measurements using crushed coal (< 1.5 mm) fed pneumatically to the bed are included for comparison.

2. Experimental procedure

The fluidised bed combustor shown schematically in Fig. 1, was 0.3 m square section and 1.83 m high and constructed from stainless steel, the walls being insulated with kaowool. The bed which was 0.6 m deep, consisted of sand of mean particle size 600 µm. Fluidising air was introduced to the bed through a bubble cap distributor plate. Crushed coal (< 1.5 mm) was fed pneumatically into the bed from a sealed hopper via a calibrated rotary valve feeder (Fig. 1). Large coal (N.C.B. 501) previously sieved to give monosized fractions (6.3, 9.5 and 12.5 mm) was fed by a vibratory feeder from a pressurised hopper to the surface of the bed. A vibratory feeding system was adopted after degradation of the coal feed occurred when a screw feeder was initially used. The large coal passed over two grids which allowed any fines present to fall through. Start up of the bed was achieved using an overbed gas burner which preheated the bed to 725 K before coal was injected. Particulate carry over in the gaseous combustion products was removed by a two-stage cyclone. Solids separated by the cyclones dropped into catchpots (Fig. 1). In order to measure the rate of elutriation of material during steady-state combustion, the carry over from the combustor was diverted into a seperate catchpot. The temperature of the bed was controlled by a cooling coil immersed in the bed. Thermocouples were located in three positions in the bed: top, middle and bottom and also in the freeboard (Fig. 1). All bed and freeboard temperatures and the cooling water temperature were recorded continuously on chart recorders.

During all the experimental runs the fluidising velocity was kept constant ($\sim 0.8\ ms^{-1}$) and changes in stoichiometry were achieved by varying the coal feed rate to the combustor. Gas samples were obtained from the bed, freeboard and exit flue by means of sampling ports located along one wall of the combustor. Water cooled stainless steel probes lined with silica were used for gas sampling. An on-line chemiluninescent analysis (TECO Model 10A) was used to determine the nitric oxide content of the combustion gas.

3. Experimental results

3.1 NO emissions

NO concentrations throughout the bed and freeboard for the crushed coal (< 1.5 mm) are shown in Fig. 2 for bed temperatures ranging between 1043 and 1193 K. A sharp increase in NO concentration is observed from 400 to 1300 ppm for a bed temperature of 1043 K and concentrations rise to 1500 ppm at the top of the bed for T_b = 1193 K. For all the bed temperatures there is a sharp decrease in NO concentration through the freeboard giving exit values of 375 ppm for T_b = 1043 K and 700 ppm for T_b = 1193 K. Similar trends are seen in Fig. 3 for the large coals (6.3, 9.5 and 12.5 mm). The concentrations of NO at the top of the bed are of the order of 1400 ppm and at the exit they have fallen to 500 ppm for a bed temperature of 1143 K. These measurements were repeated for different values of excess air (XSA) and Fig. 4 shows the variation of NO concentration at the exit flue (corrected to 3% O_2) for XSA values of between 6 and 47% for all the large coals at T_b = 1043 and 1093 K. For the 6.3 mm coal at 10% XSA and T_b = 1043 the NO concentration is 360 ppm; the corresponding value at T_b = 1093 K is 475 ppm. After these initial values the NO concentrations at both temperatures show a sharp increase to about XSA = 25% followed by a levelling off for higher values of XSA. These trends are repeated for the 9.5 mm coal but with reduced concentrations throughout. It was expected that the 12.5 mm would show a further overall decrease in NO concentration but as can be seen in Fig. 4 the 12.5 mm curve falls between those of the 6.3 and 9.5 mm coals still, however, showing the same trends as the latter two sizes.

3.2 Elutriation rates

The measured elutriation rates under steady-state conditions are shown in Figs. 5, 6 and 7. Fig. 5 shows the total carry over (i.e. ash and carbon) leaving the combustor for the 9.5 mm coal at different levels of excess air and temperature. A sharp decrease in elutriated material is observed when the level of excess air is increased from 10% to about 20%; this rate of decrease reduces as the excess air is increased beyond 20%. The carbon content of the carry over material for the 9.5 mm coal is plotted against the excess air for the four bed temperatures (Fig. 6). The proportion of carbon in the carry over decreases with increasing temperature and excess air. The same trend is observed for all the coal sizes studied (17).

The effect of coal particle size on the carry over and carbon loss at 20% excess air is indicated in Fig. 7. A sharp decrease in carry over is observed when coal sizes of increasing diameters are used in the fluidised bed combustor. Beyond the 9.5 mm coal size, elutriation rates level off and as the bed temperature increases, show an upturn (Fig. 7). This unexpected behaviour of the carry over due to the 12.5 mm coal is in parallel with the NO results for the same coal as discussed above.

3.3 Combustion efficiency

The quantity of heat lost as carbon elutriated from the combustor is the major factor affecting the efficiency of fluidised bed coal combustors. Combustion effiency has been determined for each coal particle size at about 20% excess air. The results are shown in table 1 in terms of carbon percentage combustion efficiency. Loss of carbon occurred almost entirely by elutriation.

Table 1. Combustion Efficiency as a function of coal size and bed temperature.

Temp (K)	Combustion efficiency @ 20% XSA		
	6.3 mm	9.5 mm	12.5 mm
1043	84%	88%	90%
1093	88	90	91
1143	90	92	92
1193	-	95	93

An increased carbon combustion efficiency is achieved with the increase of air up to about 20-25%, a further increase in excess air beyond this value does not improve the carbon combustion efficiency significantly. The combustion efficiency is observed to increase with bed temperature for the 6.3 and 9.5 mm coals (table 1). The 12.5 mm results show only a slight sensitivity to bed temperature (1043 K - 1193 k, 20% excess air). The highest carbon combustion efficiency of 95% is achieved with the 9.5 mm at a bed temperature of 1193 K (table 1).

4. Discussion

The levels of NO at the exit of an FBC may be expressed as a sum of the rates of formation and reduction, without specifying any mechanisms, as follows

Rate of NO emitted at the flue	=	Rate of formation in the bed	-	Rate of reduction in the bed	+	Rate of formation in the freeboard	-	Rate of reduction in the freeboard	1)
		A		B		C		D	

It is clear from Figs. 2 and 3 that A > B and D > C for all the coals used in these experiments. There are many experimental data available which show that NO reduction in an FBC can take place via NO-char reactions (8,9,10) and so the level of NO reduction may be expected to be proportional to the carbon loading in the bed, which in turn is proportional to the diameter of the coal particles in the feed. When large coal is fed to the bed the rate of NO formation will be slower and lower than for crushed coal but the rate of reduction will also be lower even for larger carbon loading because of the low carbon surface area per unit mass.

This could explain why, as shown in Figures 2 and 3, approximately the same levels of NO concentration are observed at the top of the bed for both crushed and large coals. These similar levels of NO also contradict the suggestion (11) that overbed feeding of large coal may increase NO reduction at the top of the bed due to an increased carbon loading in that region. The NO concentrations in the 0.3 m square FBC, therefore, appear to be independent of coal feed position and size of coal fed. The major portion of NO reduction reported here, takes place in the freeboard (Figs. 2 and 3). In particular the highest reduction rate occurs in the region immediately above the bed where the char concentration is high due to splashing. It is in the freeboard then that the effect of carbon loading in the bed on NO reduction is most evident since the level observed for the 9.5 mm coal are lower than for the 6.3 mm and crushed coals. The NO levels in the freeboard are seen to decrease exponentially with height (Figs. 2 and 3) in the same manner as the solids population decreases (12).

Assuming that large coal particles do not break when introduced to the bed then it would be expected that the elutriation rate would be significantly reduced compared to when crushed coal is fed to the bed. Figure 5 shows a reduction in the elutriation rate of carbon as the coal feed particle size increases but the difference is not as great as would be expected bearing in mind that the large coal is a monosized feed and does not include any fines. In particular the carbon elutriation rate for the 12.5 mm coal although initially (T_b = 1043 K) less than that measured for the 9.5 mm subsequently becomes greater for T_b > 1093 K. This may be explained by the fact that this coal (12.5 mm) in particular suffers from breakage due to thermal shock when introduced to the bed. This also explains why the NO concentrations for this coal fall between those measured for the 6.3 and 9.5 mm coals (Fig. 4). Particle attrition may also be significant within the bed (13,14,15) particularly for the larger coals. Merrick and Highley (16) derive an expression for particle size reduction due to attrition based on Rittingers Law of abrasion and showed that the shrinkage rate was proportional to the particle size viz:

$$\frac{d\,d_p}{dt} = \frac{-K}{3}\, f\,(d_p)(U - U_{mf})\, d_p \qquad 2)$$

Thus the elutriation rate for the larger coals could be significantly enhanced due to attrition phenomena. The lowest elutriation rates observed (Fig. 7) are for the 9.5 mm coal at 1193 K and 20% XSA. The effect of increasing the bed temperature and excess air will be to increase the combustion rate with a consequent reduction in the amount of carbon thrown into the freeboard. Thus the elutriation rates will decrease for an increase in both T_b and XSA. This trend can be seen in Figs. 5 and 6.

5. Conclusions

The measurements of nitric oxide concentrations in the bed and freeboard of the 0.3 m square fluidised bed have shown that nitric oxide is produced within the bed and are reduced in the freeboard. Elutriation rates and NO concentrations measured at the exit of the freeboard both decrease with increasing coal particle size up to a size of 9.5 mm for most conditions. The combustion of monosized coal particles in the fluidised bed has highlighted the interdependence of elutriation rate, bed carbon content, carbon concentration in the freeboard and nitric oxide emissions. The results also indicate that an optimum operating condition for this particular fluidised bed combustor may exist for the 9.5 mm coal size at 20% XSA. However, further experimental results are necessary, in particular with respect to the complex phenomena occurring in the freeboard region.

6. Acknowledgements

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7. Nomenclature

d_p	coal particle dia.
$f(d_p)$	fraction of coal particles in bed smaller than d_p.
H	total bed height.
K	abrasion constant.
U	superficial fluidising velocity.
U_{mf}	minimum fluidising velocity.
y	vertical co-ordinance.
ε	dimensionless height (= y/H).

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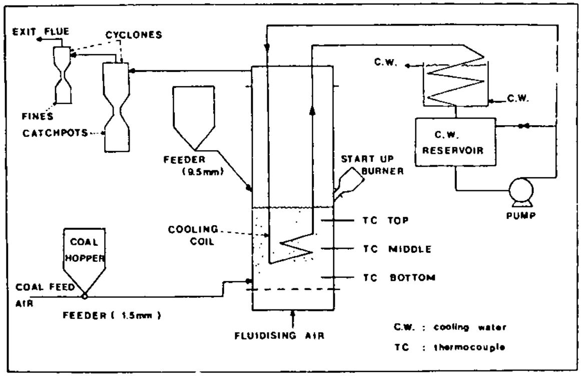
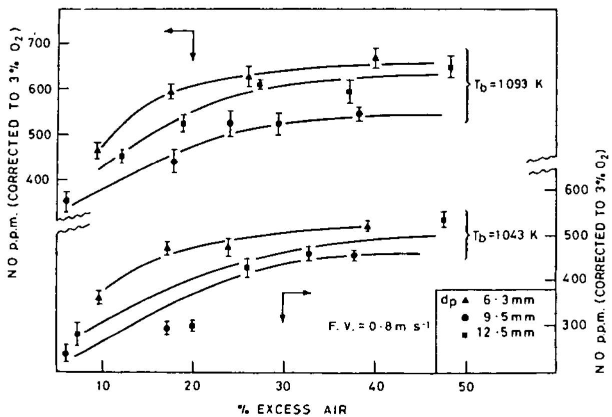


Fig. 1. (top). Fluidised bed combustor.

Fig. 2. (bottom). NO concentration as a function of excess air.



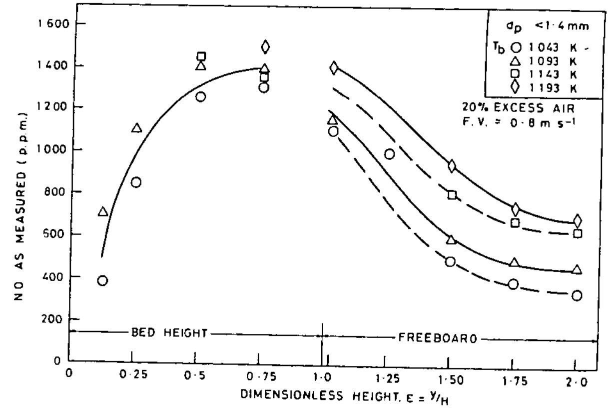
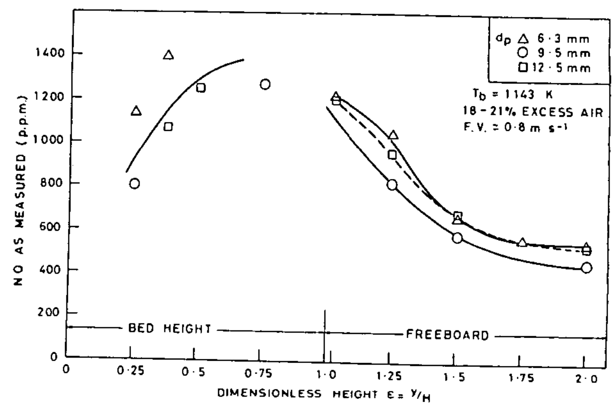
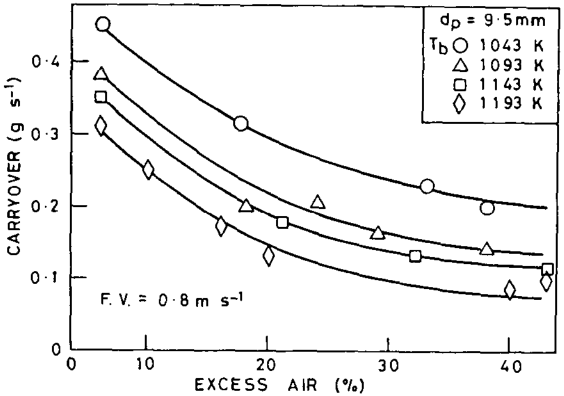


Fig. 3. (top). NO profiles for the crushed (< 1.5 mm) coal.

Fig. 4. (bottom). NO profiles for the large coals.





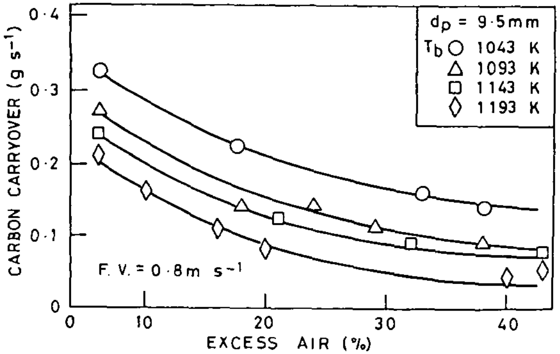


Fig. 5. (top). Carryover (carbon + ash) as a function of excess air (9.5 mm coal).

Fig. 6. (bottom). Carryover (carbon only) as a function of excess air (9.5 mm coal).

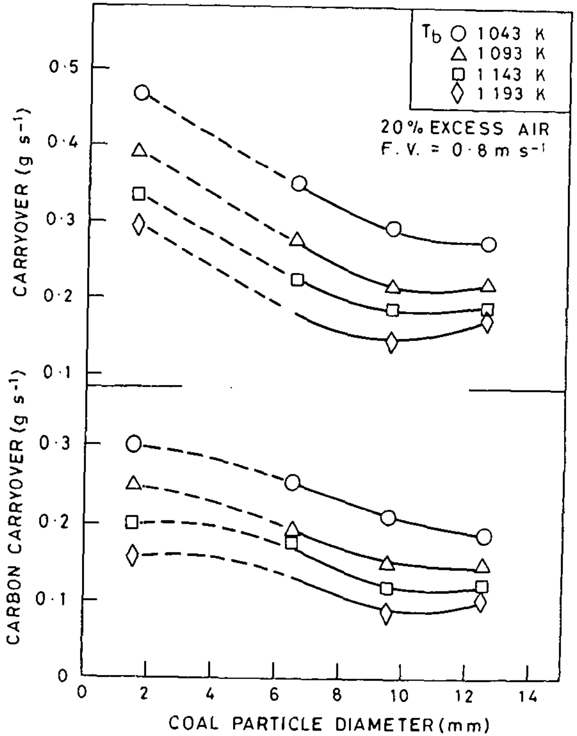


Fig. 7. Carbon and ash carryover (top) and carbon carryover only (bottom) as a function of coal particle diameter.