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CARBON ATTRITION DURING THE FLUIDIZED COMBUSTION AND GASIFICATION OF COAL

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MASTER

SUMMARY

The work during the period 1 March-31 May 1982 has been mainly directed to exploring the effect of oxygen concentration on the instantaneous rates of generation of carbon fines by attrition during the fluidized combustion of batches of 4760-6350 μm South African coal. Time-resolved bed carbon particle size distributions are determined under the same conditions as attrition experiments have been carried out. Instantaneous attrition rates have been correlated to bed carbon loading and exposed surface for various oxidizing conditions.

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1. INTRODUCTION

In the previous DOE Reports/PC-40796-1 and -2 the two-exit combustor head and the basket techniques were described. These techniques were applied to measurements of time-resolved attrition rates and particle size distributions of bed carbon during the batch fluidized combustion of a coal. Their reliability was proved by the agreement between bed carbon loading curves obtained with basket technique and those derived from carbon balance using outlet gas compositions obtained with the two-exit head combustor.

Results of preliminary experiments suggested that the correlation
$$e_c = k(U - U_o) \frac{w_c}{\bar{d}_c}$$
 holds within about the last 3/4 of the combustion cycle, e_c , k , $(U - U_o)$, w_c and $\bar{d}_c$ being, in the order, the instantaneous attrited carbon elutriation rate, an attrition constant, the fluidizing velocity excess in respect to the minimum for fluidization, the bed carbon loading and average carbon particle size. This correlation is similar to that:
$$E_c = k'(U - U_o) \frac{w_c}{\bar{d}_c}$$
 found by Donsi et al. (1981) in continuous combustion of the same coal in a 140 mm ID fluidized bed combustor, E_c being in this case the stationary attrited carbon elutriation rate. For the same bed sand size of 200-400 μm values of $k = 2.1 \cdot 10^{-7}$ and $k = 1.81 \cdot 10^{-7}$ were found in experiments of continuous and batch combustion, respectively. Note, however that whereas continuous experiments were carried out with an oxygen content which dropped from 21% at the inlet to between 8% and 0.5% at ^{the} outlet depending on air fuel ratio, batch experiments were carried out only in the range of oxygen concentration between 21% (at inlet) and 18% (at outlet). Considering that purely mechanical attrition of carbon in beds fluidized with nitrogen is one order of magnitude less fast the question arises what is the value of attrition constant k for correlating values of e_c obtained with oxygen concentration in air feed between 21% and 0%.

Experiments carried out in the last three months were directed to exploring the effects of changes of oxygen concentration in inlet fluidizing gas on carbon attrition rates, bed carbon loading and particle size distribution. The purposes were to:

- a) carry out batch combustion under average oxygen concentrations similar to those of continuous combustion with the same coal.
- b) test the $e_c = k(U - U_o) \frac{W_c}{d_c}$ correlation under different oxidizing conditions and evaluate attrition constants k .
- c) attempt to shed some light on attrition mechanism.

2. EXPERIMENTAL

2.1. Apparatus

The apparatus consists of the two bench scale fluidized bed combustors described in detail in the DOE Reports/PC-40796-1 and -2, i.e. the stainless steel combustor with two-exit head for attrition measurements, and the quartz combustor for measurements of bed carbon loading and particle size distributions with basket technique.

2.2. Procedures

Operative procedures of two-exit head and quartz combustors, and methods for working out results, were the same as those described in the DOE Report/PC 40796-1 and -2. Experiments have been carried out at 850°C, with fluidizing velocity of 80 cm s⁻¹ (at bed temperature). Silica sand 300-400 μm has been used as bed solid.

The same 4760-6350 μm nominal size South African bituminous coal previously tested has been used. For this coal, the set of data on instantaneous carbon attrition rates, bed carbon loading and particle size distribution (and the corresponding surface based bed carbon average particle size) has been completed as regards experiments with nitrogen-oxygen mixtures with oxygen concentrations of 21, 4.5, 2.9, 1.4, 0.75 and 0%. This required the performance of further experiments to obtain curves of attrition rates for nitrogen-oxygen

mixtures with oxygen concentrations of 2.9 and 0.75%, and bed carbon loading and particle size distribution for mixtures with oxygen concentrations of 4.5, 2.9, 1.4 and 0.75%.

3. RESULTS

Instantaneous rates of elutriated carbon fines e_c during the combustion are reported as a function of time in Fig. 1 for various oxidizing conditions. In this figure results already presented in DOE Report PC/40796-2 are also reported as reference. It can be seen that the peculiar trend of e_c vs t is confirmed and that the curves at oxygen percentages 2.9 and 0.75 are as expected from previous curves at higher and lower oxygen percentage. Being the contribution to elutriation of unburnt residues negligible, curves of e_c vs t substantially represent, apart from effects of post-combustion of attrited carbon, the rates of carbon fines generation due to attrition.

Table 1 gives the characteristics values of each curve, i.e. the values of: t^* the time at which relative maxima of e_c vs t curve appear; t_b the burn-out time; e_{ci} the elutriated carbon rate at $t=t_o$; e_c^* the elutriated carbon rate at $t=t^*$; W_{ci} the weight of fixed carbon charged into the bed; W_{ci}^* the weight of bed carbon at $t=t^*$; $(W_{ci} - W_c^*)/W_{ci}$ the fraction of W_{ci} burnt at t^* ; $1-\eta = \int_0^{t_b} (e_c/W_{ci}) dt$ the loss of efficiency due to elutriated carbon fines. It is worth noting that both t_b and $(1-\eta)$ increase as oxygen concentration in inlet gas decreases. This is in accordance with the general rule (D'Amore et al., 1980) that the longer the burn out time, the higher the loss of attrited carbon entrained in exit gases. Obviously, oxygen concentrations less than 0.75% would result in smaller η up to the limit $1-\eta=1$ for 0% of O_2 .

Instantaneous bed carbon loadings for all the runs, as obtained with basket technique (symbols) and from carbon balance using outlet gas composition (broken lines), are reported in Fig. 2. Granulometric analysis of the material collected with the basket gave bed carbon particle size distributions on nume-

rical and weight basis. Working out these data the surface based average carbon particle diameters $\bar{d}_c = 1/(\sum X_i/d_i)$ have been evaluated at different times. Results of these calculations are reported in Fig. 3 as $\bar{d}_c$ vs t . Solid lines fitting these values are extrapolated up to burn out time, where $\bar{d}_c = 0$. With basket technique presently used it is in fact impossible to collect particles smaller than $800 \mu\text{m}$ (DOE Reports PC/40796-1 and -2). Their influence on bed carbon loading and particle size measurements, however, becomes relevant only at high residence times.

Values of e_c vs W_c are reported in Fig. 4 to establish whether the correlation $E_c = k'W_c$ valid for continuous combustion (Donsi et al., 1981) extends also to batch operation. Values of e_c and of the corresponding W_c concern the monotone portions of e_c vs t curves, i.e. those extending over the time range from t^* to burn out time t_b . Data show that relationships e_c vs W_c significantly deviates from a straight lines. On the basis of these data one may conclude that, apart from possible significant effect of post-combustion when operating with air (21% O_2), e_c values do not greatly vary between each other, for given W_c , within the range of oxygen inlet concentration between 21 and 2.9%. It is only below this oxygen concentration that e_c appears to be strongly dependent on % O_2 .

Values of e_c are reported as a function of the product of bed carbon exposed surface and excess of gas velocity above the minimum for fluidization in Fig. 5. Results show that the correlation $e_c = k(\Pi - \Pi_o) \frac{-W_c}{\bar{d}_c}$ for continuous operation is also valid for data from batchwise combustion. Attrition rate constants k are given for each straight line. They significantly decrease in respect to the top values of $k = 1.81 \cdot 10^{-7}$ for 21% O_2 and 4.5% O_2 (and to the value of $2.1 \cdot 10^{-7}$ for continuous combustion found by Donsi et al., 1981) only when oxygen concentration is lower than 2.9%.

4. FRAGMENTATION AND ATTRITION MODELS

Previous work (Chirone, 1980; Arena et al., 1982) allowed conjecture the following fragmentation and attrition models from experiments so far carried out with the coal tested.

- 1) Fragmentation for coal size 1-3 mm or less is negligible. Attrition occurs parallelly to combustion (Fig. 6) producing fines of size δ , less than the size of elutriable coal residues d^* .
- 2) Fragmentation becomes relevant for coal size coarser than 1-3 mm, multiplying the number of residues of size d^* (Fig.7). Devolatilization is responsible for fragmentation as soon as coal is injected into the bed. Fine particles produced during fragmentation are negligible on mass basis, i.e. the amount of carbon found as elutriated fines is very small in respect to the amount of carbon found as fragments.
- 3) Not negligible carbon fines formation due to mechanical attrition at the beginning of the batch experiments, when coal particles are full of asperities, may occur parallel to carbon fines formation due to fragmentation. The amount of carbon found as fines is the sum of those formed by fragmentation and attrition at this stage.

New batch experiments with the two-exit combustor head and further experiments with basket technique presented in the DOE Reports PC/40796-1 and -2 and in this report allow confirmation of models above, shedding also some light on attrition mechanism.

- 1) The parallelism between combustion and attrition, pictorially represented for non fragmentable material in Fig. 6, is definitely proved. Carbon fines are collected throughout the combustion cycle. This is so in both the cases, coal or unfragmentable char are charged into the combustor. In the latter case any possible interference between residual effect of fragmentation on attrition occurring during combustion is prevented.
- 2) Mechanical attrition concurs significantly in determining the initial

carbon fines elutriation rate immediately after particles are charged into the bed. This is demonstrated by results of experiments in which char is used to separate the effects of fragmentation (Fig. 7 DOE Report PC/40796-1). In any case the contribution of this initial elutriation rate in respect to the overall attrited carbon within the burn-out time is negligible.

- 3) Except at the beginning of the run mechanical attrition is negligible, as shown by results of carbon fine elutriation as a function of time charging either coal or char in beds fluidized with nitrogen. Rates of elutriated carbon fines drop rapidly to a value more than one order of magnitude smaller than those averagely found under oxidizing conditions. This is likely to depend on the effects of rounding off the asperities, as shown in Fig. 8.
- 4) During the experiments under oxidizing conditions, asperities are continuously reformed because of combustion. It seems, however, that an induction time is required to achieve the optimal conditions for a large number of asperities (depending on the overall exposed surface) and their high degree of fragility (depending on how deep is the penetration of unevenness produced by combustion). A pictorial representation of these phenomena is in Fig. 9. It is interesting to note that such optimum appears to be reached when the fraction of burnt carbon is about 20% invariantly in respect to oxygen concentration (Table 1).
- 5) The fact that constant k decreases sharply only when oxygen concentration in inlet fluidizing gas falls below 2.9% suggests that the process of generation of asperities becomes controlling only below this value. For higher values, i.e. in most of conditions of interest in practical fluidization, the rate of asperity detachment appears to be controlling.
- 6) The process of asperities generation and detachment appears to be so intimately linked to the texture of ash and carbon constituents of char that considerable changes in the behaviour are likely from one coal to another.

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Fig. 1 - Elutriation rates of attrited carbon as a function of time, with reference to 3.4 g of 4760–6350 μm coal and 2 g of fixed carbon charged into the bed.

TABLE 1 - CHARACTERISTIC VALUES OF e_c vs t CURVES

4760 - 6350 μm coal ; 300 - 400 μm sand; $U = 80 \text{ cms}^{-1}$; $U_o = 2 \text{ cms}^{-1}$; $T = 850^\circ\text{C}$

INLET GAS % O_2	BED TEMPERATURE $^\circ\text{C}$	t^* min	t_b min	$e_c \cdot 10^3, \text{gmin}^{-1}$		W_c, g		$\frac{W_{ci} - W_c^*}{W_{ci}}$	$(1 - \eta)$
				$t=t_0$ e_{ci}	$t=t^*$ e_c^*	$t=t_0$ W_{ci}	$t=t^*$ W_c^*		
21	850	—	15	6.7	—	2.04	—	—	0.01
4.5	850	6.8	56	3.8	2.9	"	1.44	0.29	.04
2.9	850	10.8	84	5.6	2.7	"	1.54	.25	.05
1.4	850	18.3	160	7.6	1.6	"	1.6	.22	.06
0.75	850	32.8	375	9.0	1.4	"	1.53	.25	.11
0	850	—	—	3.4	—	"	—	—	1.00

Fig. 2 - Bed carbon loading as a function of time with reference to 3.4 g of 4760-6350 μm coal and 2 g of fixed carbon charged into the bed.

Fig. 3 - Average surface based size as a function of time, with reference to 3.4 g of 4760-6350 μm coal and 2 g of fixed carbon charged into the bed.

Fig. 4 - Instantaneous elutriation rates of attrited carbon as a function of carbon loading, with reference to 3.4 g of 4760-6350 μm coal and 2 g of fixed carbon charged into the bed.

Fig.5 = Instantaneous elutriation rates of attrited carbon vs $(U - U_0) \frac{W_c}{d_c}$, with reference to 3.4 g of 4760-6350 μm coal and 2 g of fixed carbon charged into the bed..

fraction of unconverted carbon, $1-\eta = \frac{d^{*3} + \sum_0^{d^*} n(\delta) \delta^3}{d^3}$

Fig. 6 - Carbon particle combustion with attrition.

Fig. 7 - Carbon particle combustion with attrition in presence of fragmentation generated by devolatilization.

Fig.8 - Carbon particle attrition without combustion.

Fig. 9 - Fragmentation and attrition models occurring during the fluidized combustion of a coal particle: the comparison with an e_c vs t curve.