INFLUENCE OF SOME CHARACTERISTICS OF INDIAN COALS ON FLUIDISED-BED COMBUSTION

R. K. SAHA AND P. SENGUPTA
Department of Chemical Engineering, Indian Institute of Technology, Kharagpur-721 302, INDIA

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Introduction

The primary source of fuel in India is coal, which unfortunately is of low grade with a high ash content and low calorific value. To cope with the increasing demand for power and process heat, the fluidised-bed combustor, (FBC) which can efficiently burn all types of fuel, including low-grade ones, in an environmentally acceptable way, is being developed. However, information reported in the literature about the performance of FBCs and their relationships with fuel properties is far from adequate.

One of the most important parameters in the performance of the FBC is its combustion efficiency. Apart from operational parameters such as temperature, residence time and fuel particle size, fuel reactivity also affects combustion efficiency. Fuel properties such as volatile matter and hardness contribute to fragmentation and attrition, leading to higher carbon loss. Thus, efficiency in a fluidised-bed combustion process depends on

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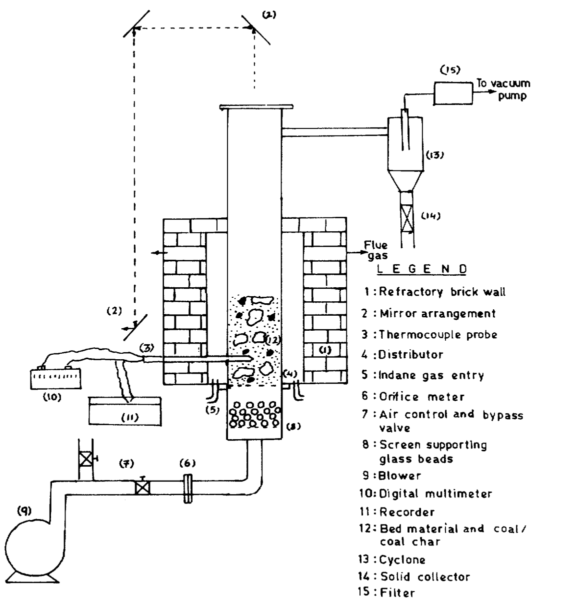

Fig. 1 Schematic diagram of batch fluidished-bed combustor

two competing processes: particle size reduction to elutriable sizes by combustion and fragmentation and attrition. Beer *et al.*[1] pointed out an interaction between the above phenomena while determining the loss of elutriated carbon particles. Chirone *et al.*[2] suggested that the rate of attrition is enhanced by combustion and vice-versa. Ikeda *et al.*[4] and others[5,7] have made attempts to relate the performance of FBCs with the coal characteristics, viz. volatile matter and fixed carbon as well as its rank, e.g. vitrinite content. The mechanism of combustion is likely to alter with changes in the type of coal/char and their properties. For high-ash coals the reactivity might be impaired due to the formation of a diffusion-resistant ash layer around the unreacted carbon core. Thus the conditions for optimum (maximum combustion efficiency) operation may vary with changes in the coal characteristics. Since coal is an extremely heterogeneous substance (Indian coals in particular), it is desirable that the most important properties that affect the FBC performances be properly identified.

This paper reports data on the burning rates as well as carbon loss for different types of Indian coal (lignite char, high-volatile bituminous coal, high-sulfur, Assam coal and high-ash washery rejects) in a batch FBC and relates them with their characteristics and operational parameters. Burning rates were measured in terms of a reactivity parameter (similar to the one used by Ivan *et al.*[5] at CANMET which inversely varies with the mean carbon conversion time, t_c.

Experimental

Set up

The apparatus used for the study is shown schematically in **Fig. 1**. The FBC is a 100 mm-diameter stainless steel (SS) column fitted with a SS distributor having a 1.6 mm diameter aperture and 1.2 percent open area. The

Table 1. Composition of fuel Used

Fuel	Weight % Dry Basis					
	Fixed *C*	Total *C*	Ash	Volatiles	FSI	HGI
Lignite Char	76.4	79.5	7.2	16.4	1.0	48.5
High-volatile sub-bituminous coal	49.5	64.4	12.6	37.9	1.5	39.5
High-sulfur Assam Coal	51.8	71.5	5.60	42.6	2.0	40.5
Washery Rejects	33.2	40.6	48.0	19.8	3.0	43.0

bed material used consisted of crushed refractory with a mean particle diameter of 0.43 mm. The static bed height was 10 cm. Air was used as the fluidising medium at superficial velocities between 8.9-18.4 cm/s at 30°C. The temperature varied between 700-900°C.

Procedure

The bed temperature was raised by burning liquified petroleum gas in the annular space between the furnace brickwall and the SS column. When it became steady, weighed quantities of coal/char were dropped into the bed. Both volatile and char burn-out times were observed visually. The coal/char sample was limited to 3-10 g per run to minimise the influence of carbon on the rise in bed temperature, reduce oxygen concentration during the combustion of volatiles and minimise the formation of carbon monoxide. The rise in bed temperature was recorded by a strip-chart recorder and the progress of combustion was monitored by noting CO_2/CO traces with time.

To reduce chemical reaction of particles elutriated from the bed, the freeboard was maintained at a temperature below 400-500°C. A 12.5-mm glass tube was fitted to the lower end of the cyclone to facilitate the collection of elutriated particles from the bed. In addition, a high-temerature filter was used to arrest the particulates in the flue gas as they come out of the cyclone.

Coal/Char particles

The coal/char particles used during the present experiment comprise: (i) high volatile sub-bituminous non-caking coal, (ii) briquetted lignite char from Neyveli, (iii) high-ash washery rejects, and (iv) high-sulfur Assam coal. For each coal/char five different fractions of narrow size ranges were prepared by crushing and carefully sieving from handpicked lumps. Densities were measured and those with considerable deviation from average values in each size group were rejected. Detailed composition of coal/coal char and other physical properties such as the hardness factor (expressed in terms of Hard Grove Grindability Index) and free swelling index (FSI), etc. are given in **Table 1**. Other details of experimental conditions are provided in **Table 2**.

Data analysis

Burning rates are measured in terms of a reactivity parameter (in bed residence time of all particles) given by

Table 2. Details of Experimental Conditions

Combustor	: Stainless Steel (SS) Column of ID 100 mm
Bed inerts	: Material- Crushed refractory Size- 0.43 mm Density- 2.1 gm/cm^3
Distributor	: SS Plate; 16-mm hole diameter, 1.12% open area
Fluidising medium	: Air
Operating bed Temperature (T) °C	:700, 800, 900
Mean particle diameter of coal char, mm	: 0.93, 2.04, 2.61, 4.34, 5.74
Mass of batch changed (gm)	: 3-10
Minimum fluidizing velocity at 30°C	: 19.5 cm/s
Fluidising velocity at 30°C, cm/s	:8.9, 12.85, 18.40

$$\bar{t}_c = \int_0^1 t\,dx \qquad (1)$$

Where dx is the fraction of total carbon converted at time t. The mean carbon conversion time is readily determined from

$$\bar{t}_c = \int_0^{t_t} (1-x)\,dt \qquad (2)$$

Where t_t, the total burn-out time, $= t_v + t_b$; t_v = volatile burn-out time and t_b = char burn-out time. The fractional burn-out, x, can be estimated from the burning rate, r, given by

$$x = \int_0^{t_t} r dt \,/ \int_0^{t_t} r dt \qquad (3)$$

The burning of coal char particles was observed visually via a mirror as shown in Fig. 1. The volatile burn-out time is defined as the time counted from the stabilisation of the flame immediately after the introduction of coal particles into the bed, to the time at which the flame is extinguished. The total burn-out time of a batch charged is identified as the time from the moment of introduction till the point when burning particles were no longer visible either in the bed or in the free-board. In addition to visual observation, burn-out time was also inferred from continuous monitoring of flue gas CO_2/CO content. A typical conbustion rate curve based on CO_2/CO trace in shown in **Fig.2**. For small-size particles, the burn-out time inferred from CO_2-trace agrees within ±3% of the visual burn-out time. However, for large-size particles a long tail in the CO_2-trace increases the burn-out time considerably above the actual values. The t_t values used here were visually observed ones. The fractional burn-out, x, can be estimated from Eq. (3).

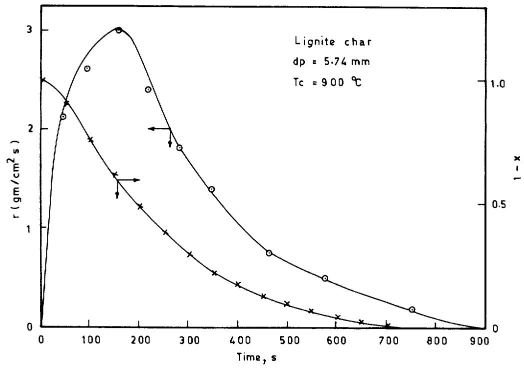

Fig. 2 Carbon burning rate and 1-f vs. time

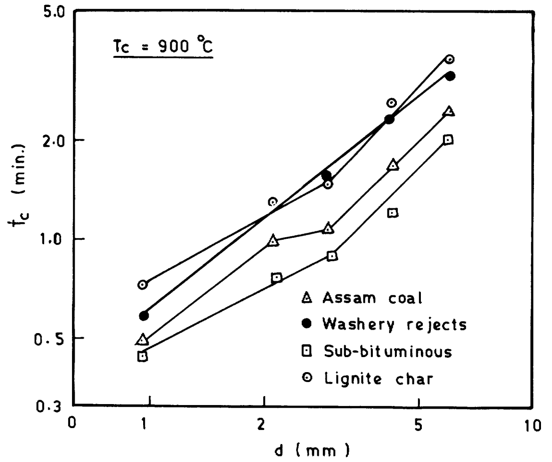

Fig. 3 Comparison of FBC reactivity of various

The carbon loss is usually estimated from the amount of fines collected in the cyclones. The fines collected in the high-temperature filter form the exit flue gas of the cyclone is small (<5% of the total solids). For small-size particles the carbon loss calculated from mass balance was found to be lower. For such cases, the measured values were reported. Four coal/coal char samples, each in five different sizes, were burnt in the FBC described previously.

Results and Discussion

Burning rate and reactivity

The overall burning rates of the selected samples were compared by calculating the reactivity parameter mean carbon conversion time, t_c, for various coal/coal char samples. Barring washery reject, all coal/chars are non-caking in nature and have a free swelling index (FSI) ranging between 1-2. The washery reject has slightly higher values of FSI and is weakly caking in nature. The mean carbon conversion time, t_c, is calculated from Eq (2), i.e. a plot of the fraction of carbon remaining unconverted versus timeplot. The fraction of carbon converted is obtained from CO_2 and CO traces

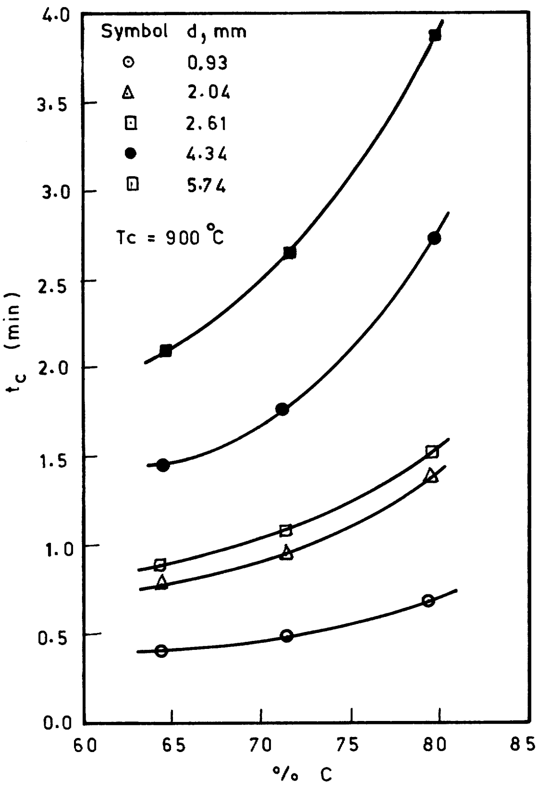

Fig. 4 Effect of carbon content on $\bar{t}_c$

with time. The effects of operating parameters of the burning rate are discussed later.

The mean carbon conversion times, obtained under similar operating conditions as a function of fuel particle sizes, are shown in **Fig. 3**. It is observed that reactivity (which varies inversely with t_c) decreases with the larger particle sizes. Barring high-ash washery reject, all coal/char appear to burn under the shrinking sphere mode. High-ash washery rejects appear to burn at constant size. It is possible that with such coals the reaction surface shrinks even if the particles do not (shrinking-core model), and that diffusion through the resulting ash layer is a significant factor. The plots of t_c against initial char particle diameter are found to obey a relation of the form:

$$t_c = a\, d_i^n \tag{4}$$

The values of n range between 0.98-1.5. Pillai[6] also studied the effect of coal/coal char on burn-out time and showed that the surface burn-out time, t_s, also exhibited a similar relationship to that given in Eq. (4). Based on the observed values of n, the mechanism governing combustion was discussed. The fact that n values in this case also are observed to change with particle diameter, indicate a shift in the mechanism of combustion, from diffusion-controlled (large size) to kinetics-controlled (lower sizes) regime of combustion.

Comparison of fuel reactivity in FBC as depicted in Fig. 3 suggests that high volatile sub-bituminous coal has the highest reactivity, indicated by its lower mean

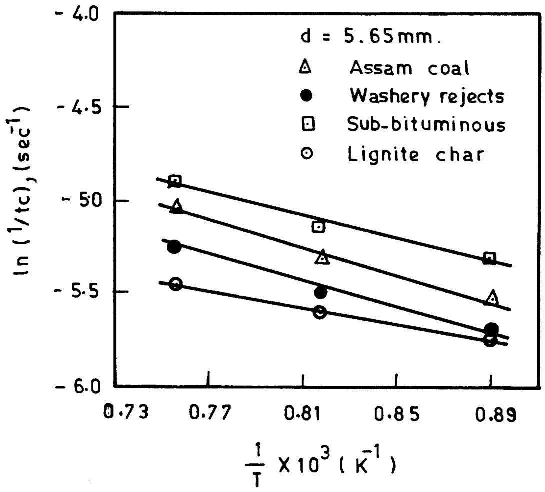

Fig. 5 Effect of bed temperature on t_c

carbon conversion time. This is followed by Assam coals and lignite char. All these coals are non-caking and have very low FSI values. Since in these cases coal plasticity is not likely to have any effect on reactivity, it is felt that mean carbon conversion time can be correlated with their carbon content. These are shown in the **Fig. 4**. Burning-rate data for high-ash washery rejects are excluded from the plots as they are observed to burn by a different mode of combustion. It is found that irrespective of particle diameter, the mean carbon conversion time increases with increase in total carbon content. Since the volatile burn-out times were determined from visual observation only and were not accurate to the desired extent, no attempts were made to calculate the mean carbon conversion time due to fixed carbon and correlate it with the fuel particle sizes.

High-ash washery reject has higher FSI values than other coals tested here. The fuel composition and FSI value for the raw coal are not known. Thus, the effect of coal ash on plastic property could not be assessed. Though the coal has the lowest carbon content and comparitively higher FSI value, it is less reactive than high-volatile bituminous and high-sulfur Assam coals. Combustion rate studies using the basket technique and visual observation of partly burnt char indicate that combustion occurs at constant diameter and diffusion through the product ash layer appears to impair its reactivity.

Effect of bed temperature

Figure 5 shows the plot of ln $(1/t_c)$ versus $(1/T)$ to consider the effect of bed temperature on the reactivity of coal char. The mean t_c values are reduced by about 26-37% as the bed temperature increases from 700-900°C. Thus, despite changes in coal char types, reactivity generally increases with increase in bed temperature. This is at variance with the result of Ivan *et al.*[5] who reported that, except for coke, temperature has not much effect on the coal char tested.

The slopes of the curve, which are a measure of

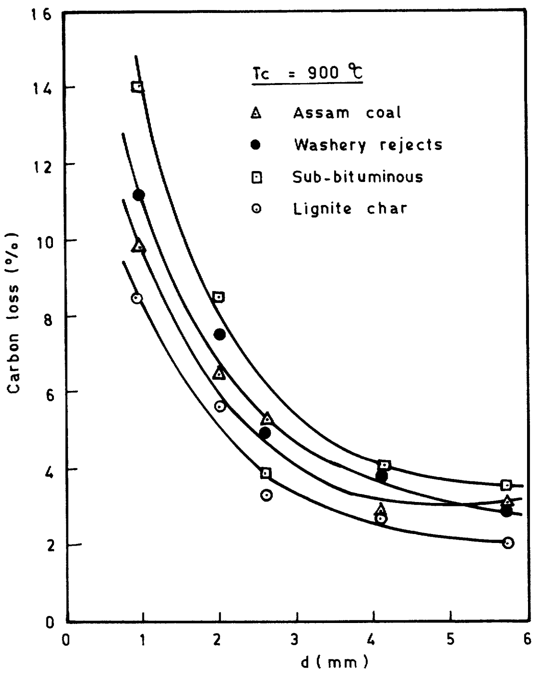

Fig. 6 Comparison of carbon loss of various fuels

activation energy, vary between 18,700 to 27,100 KCal $Kmol^{-1}$. These values appear to be quite low. Smith[8] suggested an activation energy for pure carbon of 59.8 KCal mol^{-1} while Walker *et al.*[9] reported a value of 61 ±3 KCal mol^{-1}. The present result is though, consistent with the trend that for impure carbon the activation energy should be lower; it appears to be too low, indicating probably that a diffusion regime prevails during the combustion process.

Carbon loss

As stated earlier, the fines collected from the cyclone cannot be measured with sufficient accuracy. However, they provide qualitative information for interpreting results. The effect of particle size on carbon loss for different types of coal/coal char is shown in **Fig. 6**. It is the total carbon loss (including the losses due to C in the exit flue gas). It is found that the carbon loss decreases with increase in the particle sizes.

The implications of combustion rate and reactivity on carbon loss and efficiency are difficult to assess. Though high combustion rate and reactivity bring about low carbon concentration in the bed and generally should lead to higher combustion efficiency, in reality it is elutriated carbon loss from the bed that is the determining factor. Elutriable fine sizes may be generated either by combustion of original coal/coal char particles or fragmentation and attrition during devolatilization and combustion process. The fragmentation and attrition of coal/char are affected, among other factors, by hardness and swelling index.

Thus carbon losses from a FBC are due to a combination of interacting factors as discussed above. Fuel reactivity is not the only factor in determining carbon losses and, therefore, combustion efficiency. In the present case of Fig. 6, coal having the highest reactivity (sub-bituminous) appears to have the highest carbon loss as well. It is significant that this coal has the highest Hard Grove Grindability index, i.e. is the softest among all the coals tested, though for other coal/char, it shows no definite trend on the carbon loss. Apart from fuel reactivity, it is the extent of fines generated in the bed and their size distribution as well as the residence time distribution that will affect the carbon loss and efficiency in FBC.

Conclusions

Four Indian coal/coal chars (including a washery reject) were tested in a batch FBC to evaluate the effect of fuel properties and operational parameters (temperature and particle size) on the combustor performance. Fuel reactivity increases with bed temperature but decreases with particle size. Of the fuels tested, leaving out high-ash washery rejects, reactivity could be related with the carbon content and is found to decrease with it. Higher reactivity of coal/coal char may not necessarily lead to higher combustion efficiency, and it may be adversely affected by other properties such as volatile matter and hardness.

Nomenclature

d	=	particle diameter	[cm]
t	=	time of combustion	[s]
t_b	=	char burn-out time	[s]
t_c	=	mean carbon conversion time	[s,m]
t_t	=	total burn-out time	[s]
t_v	=	volatile burn-out time	[s]
T_c	=	bed temperature	[°C]
r	=	burning rate	[gm/cm^2 s]
x	=	fractional burn-out	

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