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DEVELOPMENT OF REACTIVITY PARAMETERS FOR CHARACTERIZATION OF COAL IN FLUIDIZED BED COMBUSTION

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ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
DIVISION REPORT ERP/ERL 86-36(OP)

32 pg

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by

I.T. Lau*

ABSTRACT

A new method to measure apparent reactivity, which accounts for all the effects of coal type on reaction kinetics in fluidized bed combustion (FBC), has been developed to characterize and rank various coals according to overall burning rates in a fluidized bed environment.

This method estimates FBC reactivity by means of a parameter called mean carbon conversion time, which can be related to the carbon inventory of practical FBC systems. An easy and rapid experimental technique, which burns coal batchwise in a bench-scale fluidized bed combustor, has been developed to determine the mean carbon conversion time.

This technique was employed to examine five different coals and rank them according to FBC reactivity. To differentiate between devolatilization and char combustion, a turning point on the experimental burning rate curve was used instead of the common method of observing the volatile flame. Char mean carbon conversion times were also measured and compared.

The effects of coal particle size and bed temperature on FBC reactivity and combustion efficiency and the effects of particle fragmentation on experimental results were investigated. Efforts were made to correlate the FBC reactivity with other coal parameters such as volatile content, carbon content and free swelling index.

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INTRODUCTION

It is well known that a fluidized bed combustion (FBC) system has the ability to burn a wide range of coals. Many low-grade fuels which fail to burn satisfactorily in conventional boilers can be readily burnt in a fluidized bed where good mixing and long residence time ensure good combustion efficiencies. It is expected in the near future that many coals, with a wide variety of properties, will be burnt utilizing this promising alternative combustion technology.

Coal type has been shown by many workers to be an important factor in determining the combustion efficiency of FBC systems (1,2). For example, the burning of extremely low quality coal in China has presented some boiler design problems (3,4). Therefore, understanding the coal's combustion characteristics and their effect on FBC processes is highly desirable in design calculation and operation optimization. To date, such correlations are seldom available, as it has not been possible to successfully predict the combustion performance of any fuel simply on the basis of its properties.

One of coal's major characteristics is its reactivity, which is important in determining the residence time required for complete combustion in FBC systems. In turn, conversion time determines bed carbon inventory which is an important factor in determining unburned carbon loss (5). In FBC systems this occurs via both bed materials withdrawal and elutriation of attritted fines. Reactivities are commonly measured with fixed bed reactor, entrained bed reactor, and thermogravimetric techniques. Because char combustion is much slower than that of volatiles, for simplicity most measurements focus on char reactivity and neglect volatiles. Intrinsic char reactivities, defined as the burning rate per unit pore surface area in the absence of restriction due to diffusion, are given by some workers (6,7). However, in practice, the intra-particle processes of pore diffusion and chemical reaction are combined into a single rate expression to represent an apparent reactivity based on particle external surface area.

Estimating coal burnout time from char reactivity data to predict combustion efficiency requires a reliable complete model. Unfortunately, despite considerable research on the reaction kinetics of FBC, certain areas remain unresolved or subject to controversy. Also, because char properties depend on the parent coal's thermal treatment conditions, char reactivity measured by conventional techniques may be significantly different from that of the in situ FBC environment. Besides the chemical reaction, the overall combustion kinetics are complicated by other processes such as fragmentation and attrition, which are governed by coal properties. Paradoxically, a coal of higher char reactivity may burn more slowly than one of lower char reactivity because of different coal properties.

When coals are ranked directly according to the overall combustion rates in a fluidizing environment, an apparent FBC reactivity is introduced. This newly defined reactivity involves all the effects of coal type on burning rate so that the FBC behaviour of coal can be more easily identified and characterized. The direct measurement of the overall reaction kinetics in FBC systems also provides valuable information for fluidized bed carbon inventory estimation.

The major objective of this work was to develop an experimental method to measure and rank various coals in terms of this novel FBC reactivity parameter. Further, it is hoped that, from experimental kinetic studies, the relations between coal properties and combustion performance, and some major uncertainties in the reaction mechanism in FBC can be elucidated.

DEVELOPMENT OF REACTIVITY MEASUREMENT

Basic Considerations

To measure FBC reactivity of coal it is necessary to develop an experimental technique which is easy, rapid, and requires uncomplicated equipment utilizing a small amount of fuel to provide combustion kinetics and burning history information. Also, it is desired that experiments to measure kinetics can be designed to simulate the FBC design and operation, particularly involving processes such as fragmentation and attrition. To this end, a small bench scale fluidizing unit to be operated in a batchwise mode was designed and built.

Because the combustion rate in the fluidized bed is a function of coal type, particle size, and conditions in the bed, relative FBC reactivity measurements should be based on identical coal size and operating conditions. Most previous FBC kinetic studies, in which a single spherical non-volatile carbon particle was burned, measured particle burnout time or particle weight loss with time. The resulting data can be interpreted by gas-solid reaction theories without the complications introduced by volatiles or the combustion of other particles. However, such simple experimental techniques cannot fulfill the requirements of the present FBC reactivity measurement.

Coal instead of char should be fed into the fluidized bed so that reactions involve in situ burning effects from processes such as devolatilization, particle swelling, and fragmentation. Also, because characteristics of different coal sizes may vary, it is necessary to use particle sizes as close as possible to those in practical FBC. It is impractical to use single particles for experiments on fine size coals, and, even for large particles, many coals are likely to shatter in the fluidized bed so that the advantage of feeding single particles vanishes.

Measuring particle weight loss in various combustion stages is difficult when fine combustibles are retrieved from bed materials. Conversely, measuring burnout time from a multiparticle system gives results dominated by particles with the longest burnout time. Another difficulty is that particles in a narrow size range sample charge may have different shapes and sizes, and may be subject to different combustion environments at various times. Other differences among particles are created by fragmentation after which the largest char particle left in the bed most likely disappears last and is responsible for the long tailing of the burning curve. Examples of unexpected and contradictory results from preliminary experiments where burnout times were measured are given elsewhere (8).

A parameter, which should characterize the combustion kinetics covering the entire burning period of every coal particle in the bed, is desirable to provide a measure of FBC reactivity for various coals. The overall burnout time and time average burning rate are too strongly dependent on the largest particle in the bed and do not satisfy the requirement discussed above. Consequently, a parameter which is more meaningful in statistically representing the burning rate of the whole batch of coal particles was chosen as the FBC reactivity index. This parameter is the mean residence time of carbon burnt in the bed and is called the mean carbon conversion time, $\bar{t}_c$, hereafter. The value of $\bar{t}_c$ can be obtained readily from the overall burning rate data and is directly applicable for carbon inventory estimation of practical FBC systems without complicated model calculations. The relationship between mean carbon conversion time and carbon inventory of a continuous fluidized combustor is illustrated below.

For a practical continuous FBC system, the carbon inventory in the fluidized bed is equal to the product of the carbon feed rate and the mean carbon residence time,

$$W = F\,\bar{t} \tag{1}$$

Assuming all converted carbon leaves the system immediately as gaseous products, the carbon balance at steady state can be written as:

$$\underset{\substack{\text{Carbon feed}\\ \text{rate}}}{F} = \underset{\substack{\text{Carbon conversion}\\ \text{rate}}}{R_c} + \underset{\substack{\text{Carbon elutriation}\\ \text{rate}}}{R_e} + \underset{\substack{\text{Carbon withdrawal}\\ \text{rate}}}{R_d} \tag{2}$$

Therefore, the mean carbon residence time in the bed can be represented by the sum of the fractional mean residence time of the three outlet streams,

$$\bar{t} = f_c\,\bar{t}_c + f_e\,\bar{t}_e + f_d\,\bar{t}_d \tag{3}$$

or, by combining the two carbon loss terms into one,

$$\bar{t} = \varepsilon\,\bar{t}_c + (1-\varepsilon)\,\bar{t}_l \tag{4}$$

where ε is the carbon combustion efficiency, $\bar{t}_c$ and $\bar{t}_l$ are the mean carbon residence time for the fractions of conversion and loss respectively.

The evaluation of $\bar{t}_l$ requires knowledge of the elutriation rate, bed mixing intensity, and the feed point and withdrawal point locations. These are highly dependent on individual combustor design and their determination is not within the scope of this work. When no carbon loss rate information is available, bed carbon inventory can still be estimated by the approximation $\bar{t} \simeq \bar{t}_c$ since in most cases the value $1-\varepsilon$ is usually small.

Of course, applying the $\bar{t}_c$ values measured from a particular laboratory scale apparatus to carbon inventory estimation for a practical FBC system is not simple and requires a factor to correct for the differences in operating conditions and scale. However, the relative values of FBC reactivity can be used to provide a comparison of the desired coal fuel to one with known carbon inventory, so that the combustion performance can be predicted.

Parameter Measuring Technique

With the above in mind and the requirement that the parameter measuring technique be simple and easy to run, an experimental method has been developed for evaluating the mean carbon conversion time by monitoring the flue gas composition during combustion of coal.

From the traces of carbon monoxide and carbon dioxide concentrations in the flue gas, the molar carbon burning rate can be obtained from the equation:

$$\frac{dn}{dt} = UA\,(C_{CO} + C_{CO_2}) \tag{5}$$

By assuming the amount of gas flowing through the system does not change significantly, integration of Equation 5 gives the amount of carbon burnt at any time t:

$$n = UA \int_o^t (C_{CO} + C_{CO_2})\,dt \tag{6}$$

At $t = t_B$, the overall burnout time, $n = N$, the total amount of carbon burnt.

$$N = UA \int_o^{t_B} (C_{CO} + C_{CO_2})\,dt \tag{7}$$

The expression for the mean carbon conversion time is:

$$\bar{t}_c = \int_o^1 t\,d\,f$$

or

$$\bar{t}_c = \int_o^{t_B} (1 - f)dt = \int_o^{t_B} (1 - \frac{n}{N})dt \tag{8}$$

Graphical integration can be employed to evaluate Equations 6 and 7 to estimate the values of n and N which are then substituted into Equation 8 to calculate $\bar{t}_c$.

With minor modification, the above equations can also be used to estimate the mean fixed carbon conversion time, $\bar{t}_{ch}$, for char combustion provided that the processes of devolatilization and char burning can be distinguished. In such calculations, the ignition times of solid char rather than coal volatiles were considered as the initial time zero. The upper integral limits for Equations 7 and 8 were replaced by the char burnout time, $t_B - t_v$.

Similarly, Equations 1 to 4 can be applied to char combustion by simply replacing all terms representing coal by char when the relation between fixed carbon inventory and $\bar{t}_{ch}$ is required.

The value of fixed carbon inventory is an important parameter in determining combustion efficiency. According to Arena et al. (9), the main source of elutriated carbon is the fines generated by the attrition of char surface by abrasion, and attrition rate is directly proportional to the fixed carbon inventory in the bed.

$$R_a = k\ (U-U_{mf})\ \frac{W_{ch}}{\bar{d}} \tag{9}$$

EXPERIMENTAL

Equipment Description

The apparatus consists of a stainless steel combustor 0.1 m ID and 1.17 m high, built specifically for the FBC reactivity measurement. The combustor is heated by external electrical elements which are divided into four individually controlled sections. Pressure and temperature probes were inserted at various locations throughout the combustor.

Fluidizing gas, which may be air or an air-nitrogen mixture, is preheated to about 600-700°C before being passed through a perforated distributor into the bed. Solid fuel can be charged through a viewport-feeder assembly located just above the maximum fluidized bed height. The feeder consists of two ball valves and a pneumatic line which supplies an air jet to ensure that all the coal sample enters the combustor.

The flue gas is emitted to the atmosphere via a cyclone and a sample is continuously withdrawn and cleaned before being passed to the analyzer bank to determine its composition. CO and CO_2 concentrations are measured by infrared analyzers and a paramagnetic analyzer is used for oxygen measurement. The analog signals generated from the gas analyzers, thermocouples, and pressure transducers, etc., are converted to digital form by a data acquisition system and then stored and analyzed by a mini computer. A schematic of the equipment is given in Fig. 1. Equipment details and design are given elsewhere (8).

Materials and Procedure

The fluidized bed is composed of about 1.5 kg of silica sand with a mean size of 0.5 mm. Table 1 provides the ranks of the five coals studied. Coal D, is from the US, all others are Canadian.

Coal samples received had a wide particle size distribution. To allow a comparison of experimental results between the coal based on the same particle size and to eliminate the particle size effect on FBC reactivity measurement, coals from 0.6 mm to 25.4 mm were screened into five size fractions. Their size ranges are given in Table 1. The proportion of coal particles larger than 25.4 mm and smaller than 0.6 mm, is usually small and their properties are assumed to be the same as those of their closest size fractions. Since the size ranges of the two largest fractions are too wide to produce consistent reactivity measurements, only particle sizes close to 13 mm and 7.2 mm were selected to represent the fraction of sizes 1 and 2 respectively for combustion experiments.

Proximate and ultimate analyses were obtained for all size fractions of each coal but only information considered to relate to FBC reactivity is listed (together with the measured free swelling index) in Table 2.

For most experiments the fluidized sand bed was preheated electrically to 1043 K and air flow at superficial velocity of about 0.6 m/s through the combustor. Preheated bed temperatures from 938 to 1123 K were set for experiments designed to examine temperature effect. The lower bed temperature range is less than that used in most practical fluidized combustion units (1123 K plus) but helps to distinguish coals with close reactivities because the effect of temperature on burning rate varies with coal type. This is discussed below. Freeboard temperature was controlled to a lower value, usually below 873 K, to minimize combustion reaction in this zone.

In order to clearly observe a volatile flame, thus allowing the processes of devolatilization and char burning to be decoupled, air was used as fluidizing medium. A weighed coal sample of 10 g was fed through the pneumatic double valve feeder into the preheated bed zone. The flue gas compositions and bed temperature were recorded continuously until CO and CO_2 concentrations returned to zero. Specially written computer programs run on a mini computer were then used to analyze data, calculate results, and plot appropriate combustion curves.

RESULTS AND DISCUSSIONS

Visual Observations

When charged into the hot fluidized bed, all coal particles ignited immediately and volatile flames were observed through the viewport during the early stage of combustion. In some cases the flame enclosed particles stayed afloat on top of the bed as reported previously (10,11) but bounced with the circulated sand particles and occasionally disappeared into the bed in other cases. It seems that the induced solid circulation produced by bubble flow was high enough to drag devolatilizing coal particles into the bed.

Particle fragmentation was detected by observing coal particle size distribution in the bed. Although most breakages are believed to occur as the result of thermal fragmentation during devolatilization, this may also happen to some char particles. In a FBC system with fixed conditions the extent of fragmentation of each particle is a function of the coal type, size, shape, and burning history. Coals in the same batch sample of narrow particle sizes range may behave differently and hence create a wide size distribution in the fluidized bed. It is not unusual to observe only one or two char particles with sizes of a few millimetres burning at the final burning stage of some experiments.

Bright fine "combustibles" blown out of the bed surface, which are then extinguished in the cold freeboard zone, can be seen over the entire combustion period. Most of the elutriated particles during char combustion are probably produced from attrition. However, carbon loss due to elutriation seems most severe when volatiles are released although no quantitative measurement has yet verified this conclusion.

Flue Gas Composition

Typical flue gas compositions obtained when burning large particle sizes (over 3 mm diam.) are shown in Fig. 2a. A high carbon dioxide peak together with or without a much smaller carbon monoxide peak at the beginning of combustion indicates the vigorous burning of evolved volatiles. Both peaks appear to have higher values when burning small coal particle sizes (under

3 mm diam.) as shown in Fig. 2b. Depletion of oxygen concentration shown in these figures indicates an upset in operating conditions, especially during initial release of volatiles. This happened frequently with the present small scale apparatus and this phenomena restricted the coal sample size used. The faster reaction due to burning smaller coal particles provided a more significant upset in the oxygen partial pressure and hence a larger proportion of carbon converted to CO due to oxygen starvation. In addition, carbon monoxide may also be formed by incomplete combustion of elutriated fines in the freeboard where a lower temperature condition prevailed.

Carbon monoxide may appear a second time, as shown in Fig. 2a, during char combustion and remains at a small asymptotically decreasing level until total carbon burnout in the bed. The proportional amount of carbon to form CO presented by the second peak, in contrast to that presented by the first peak, decreases slightly with decreasing coal particle size. The magnitude of this second CO peak unlike the first, is very sensitive to bed temperature. Figure 3 shows the temperature effect on CO formation.

Carbon Burning Rate

The flue gas composition data can be used to calculate carbon burning rate using Equation 5. The results obtained from burning large coal particle sizes are given in Fig. 4a. The curve illustrates an obvious combustion rate turning point at time t_v. This was found to match closely the observed flame time during experiments. Thus the time, t_v, is considered to be the volatile evolution time, or, the time after which char combustion commences.

Figure 4b gives the burning rate of coal particles in the small size range. The curve shows that the rate of carbon reaction decreases gradually with no sudden turning point as shown by the previous graph for large particles. A small sized coal particle evolves only limited amount of volatile matter and this is not enough to stop the oxygen from penetrating to the solid surface. Hence, fixed carbon ignites before completion of devolatilization so that the two burning processes overlap and cannot be treated independently.

The burning rate curves, similar to the previously given flue gas composition curves, characterize combustion behaviour of various coals burned in fluidized beds. The shape, volatile peak height, etc. of the curves can provide information on both volatile and char combustion details.

Mean Carbon Conversion Time

Mean carbon conversion times of five coals divided into five size fractions were calculated from the flue gas concentration data and are given in Fig. 5. The effect of particle size on FBC reactivity is also shown. In plotting this figure, the intermediate value between size range limits was used for the three small size fractions, and, for repeated experimental runs, the results were averaged. The standard deviation ranged from 0.05 min for smallest particles to 0.46 min for the largest.

Figure 5 shows that the FBC reactivity orders for coals of the first four size fractions, sizes 1 to 4, are very similar and the coals can be ranked as D,E>G,C>B. However, the order of the finest size fraction, which may be considered closer to the order of the apparent reactivity based on external surface area measured by conventional techniques, is E>G>C>D>B.

As reaction kinetics is a strong function of temperature, changing the bed temperature for low reactivity coal, for which chemical kinetics are important, should result in different values of mean carbon conversion time. Such a temperature effect on FBC reactivity has been demonstrated by experiments involving coal B, the most unreactive coal among the five studied. The results shown in Fig. 6 are given in terms of the fractional change of $\bar{t}_c$ resulting from a 50 K increase in bed temperature. At the other extreme, combustion of the very reactive coal D is apparently dominated by mass transfer control and the effect of temperature appears to be small.

It is surprising that the temperature effect on $\bar{t}_c$ is insensitive to coal particle size. As the mass transfer coefficient is inversely related to particle size, chemical kinetics and hence bed temperature, should be more important when burning smaller diameter particles. Similarly, the effect of coal type does not appear to be influenced much by particle size even though the $\bar{t}_c$ value is a strong function of particle size as shown in Fig. 5.

Coal feed usually covers a wide range of particle size distributions for most FBC systems. Because $\bar{t}_c$ values are measured for narrow particle size fractions to allow comparison among coals, a mean value is required and this can be estimated from the $\bar{t}_c$ values of all fractions and the particle size distribution of the feed used in practical application.

$$\bar{t}_c = \Sigma\, f_i\, \bar{t}_{c_i} \qquad (10)$$

Mean Fixed Carbon Conversion Time

The values of mean fixed carbon conversion time for char are given in Fig. 7 for the five coals and three size ranges. The $\bar{t}_{ch}$ values were obtained using the turning points on the burning rate curves as zero time. Therefore, only results from the three large size fractions are available. Results show that the order of the FBC char reactivities for the five coals is not much different from that of the parent coal except that char E is more reactive than char D. There is no difference in FBC reactivity order between size fractions of these chars and they can be ranked as $E > D > G, C > B$.

Similar to their parent coals, changing the bed temperature affects the mean carbon conversion time of each char. By excluding volatiles, the fractional change of $\bar{t}_{ch}$ value is about 10% less than that of $\bar{t}_c$. Again, the temperature effects on $\bar{t}_{ch}$ are relatively insensitive to the different particle size fractions.

Elutriated Carbon Loss

It was difficult to measure accurately the amount of carbon loss from fines collected in the cyclone with the simple equipment and small coal samples. To compare the carbon loss among coals, which is reported to depend on reactivity (12), the combustible loss in each experiment was calculated from carbon balance based on flue gas carbon concentration:

$$E = (1 - \frac{N}{XW_c/M}) \times 100 \qquad (11)$$

Where the fractional carbon content in coal, X, can be obtained from coal analysis, and the total amount of carbon burnt, N, can be evaluated from Equation 7.

Results in Table 3 show the elutriated carbon loss decreases with increasing coal particle size as expected.

According to Chirone et al. fines generated from char attrition are the main source of elutriated combustibles (5). A high combustion efficiency should therefore be expected when burning coals of high FBC reactivity. Combustion results for coal D in Table 3 and Fig. 5 show that only the finest particles are relatively unreactive and burn with relatively high carbon loss compared with the results for other coals. Thus the trend discussed above was followed. However, no such agreement is shown in the combustion results for the other coals. As indicated in Equation 9 attrition rates are proportional to carbon inventory and inversely proportional to mean char particle size. Either fragmentation, which creates large differences in char particle size among various coals, or, a similar process, which generates more elutriable fines than attrition, must occur when burning these coals in fluidized beds. This would suggest that particle fragmentation and the way solids break are major factors in determining performance at least for fluidized bed combustion of many lignite and bituminous coals.

Changing the bed temperature had little influence on carbon loss of the five coals. In some experiments lower carbon loss was obtained from lowering the bed temperature. To ensure that experiments had similar oxygen partial pressure conditions, air flowrates were not adjusted when using different bed temperatures for some experiments. It is therefore possible that the higher fluidizing gas velocity resulting from the higher bed temperature caused the elutriation of more fine combustibles and this caused the higher carbon loss observed at higher temperatures. Although bed temperature has little effect on elutriated combustible loss, a significant amount of heat will be lost by unburnt CO at low bed temperatures.

By assuming the amount of in situ fixed carbon in the char during combustion equals that measured from proximate analysis, a balance of fixed carbon from char burning data shows that the degree of fixed carbon loss is consistently higher than that of total carbon loss. These anomalies are believed to have resulted because some of the burnt fixed carbons were treated as volatiles during devolatilization rather than char in the fixed carbon balance calculations. Ignition on some parts of the char surface before devolatilization was complete plus the effect of gas diffusion in the sampling system may have caused overlapping of the signals indicating volatile and char combustion. The turning point on the burning rate curve probably represents the end limit of the overlap where volatiles vanish, thus a certain amount of fixed carbon was lost in balance calculations. In addition, fragmentation during devolatilization may create a wide particle size distribution when small char particles ignite during evolution of volatiles from large particles. Therefore, some fixed carbons are consumed during devolatilization. Despite this apparent error, the use of the turning point, which is considered close to the overlap end limit as the char combustion period begins may be justified because the kinetic study of gas-solid reactions in this period should avoid complications introduced by volatiles combustion.

Effects of Coal Type

Coal properties are expected to be a major factor affecting FBC burning rate and combustion performance. However, the interrelated processes make it difficult to determine the relation between FBC reactivity and various coal properties. Only a limited qualitative analysis of the effects of coal type is presented.

Because volatiles burn much faster than char and ignite more easily the volatile content is expected to be one of the most important coal properties influencing mean carbon conversion time. Furthermore, evolution of volatiles may enlarge solid pore size and increase the char reactivity. Experimental results show that coal B, having the lowest volatiles, has the lowest FBC reactivities for both coal and char. Coal E, having the highest volatiles, has the smallest char mean carbon conversion time as expected. However, despite having less volatiles and lower char FBC reactivity than coal E, coal D has the smallest $\bar{t}_c$ values for some size fractions. By examining the burning rate curves it was found that coal D gave the highest volatile peaks. Probably significant amounts of fragmented small char particles burned during devolatilization and this helped to keep the $\bar{t}_c$ values low.

Perhaps the best "coal type" correlation with the present FBC reactivity results is the one obtained from the coal's carbon content. Figure 8a to d shows that, except for coal D, FBC reactivity decreases with increasing carbon content. The exceptional fast burning rate of coal D may be caused by its high free swelling index which usually means high char porosity. Only the highly oxidized finest sized particles lost their high FSI value and burned at a rate similar to the other coals as shown in Fig. 8e.

CONCLUSIONS

1. A new method of measuring apparent reactivity is introduced to characterize and to rank coals according to their overall burning rate in a fluidized bed environment.

2. A combustion rate parameter called mean carbon conversion time was found more suitable than the commonly employed burnout time for use as the reactivity parameter for FBC systems. A simple experimental technique has been developed to measure this reactivity parameter. The measuring technique can be carried out rapidly and with small scale apparatus, and is suitable for development into a standard method to rank various coals and evaluate mean carbon conversion times for combustion efficiency estimations.
3. Turning points on experimental burning curves were used to divide devolatilization and char combustion zones so that the mean carbon conversion times for both coal and char can be estimated.
4. Overlap occurred between the processes of volatile and char combustion even when large coal particles were burned.
5. There are no major differences in FBC reactivities ranking between coal and char, and between various size fractions except for the finest coal size fraction of the five coals studied.
6. Changing bed temperature affects the FBC reactivities of various coals to different degrees and tends to have a greater effect on less reactive coals.
7. The values of mean carbon conversion times for both coal and char increase with increasing coal particle size, but the temperature effect and "coal type" effect on $\bar{t}_c$ and $\bar{t}_{ch}$ values are not sensitive to particle size.
8. Experimental results suggest that particle fragmentation appears to be as important as char attrition in determining elutriated carbon loss.
9. Changing bed temperature has no significant effect on elutriated carbon loss for the five coals burnt under present operating conditions.
10. The relationship of carbon content in the coals to FBC reactivity gives the best "coal type" correlation for the present FBC reactivity results. The mean carbon conversion time generally increases with increasing carbon content, except for coals with high free swelling index which are more reactive than would otherwise be expected.

ACKNOWLEDGEMENT

The author acknowledges with thanks F.D. Friedrich and E.J. Anthony for continued support and helpful suggestions for this work. M.D. Romanow is also acknowledged for operation of equipment.

NOMENCLATURE

A = bed cross section, m^2

$\bar{d}$ = mean char particle size, m

E = elutriated carbon loss, %

f = fraction carbon burnt

f_c, f_d, f_e = carbon conversion, withdrawal, and elutriation fractions

F = carbon feed rate, g/min.

C_{CO} = carbon monoxide concentration g-mole/m^3

C_{CO_2} = carbon dioxide concentration, g-mole/m^3

k = attrition rate constant

M = carbon molecular weight

n = amount carbon burnt, g-mole

N = total amount carbon burnt, g-mole

R_a = carbon attrition rate, g/min

R_c, R_d, R_e = carbon conversion, withdrawal, and elutriation rates, g/min

t = time, min

t_B = overall burnout time, min

$\bar{t}$ = mean carbon residence time, min

$\bar{t}_c$, $\bar{t}_{ch}$ = mean carbon conversion times for coal and char, min

$\bar{t}_d$, $\bar{t}_e$, $\bar{t}_l$ = mean withdrawal, elutriation, and overall loss carbon residence times, min

t_v = devolatilization time, min

U = gas superficial velocity, m/min

U_{mf} = minimum fluidization velocity, m/min

W = carbon inventory in bed, g

W_c = coal sample size, g

W_{ch} = fixed carbon inventory in bed, g

X = fractional carbon content in coal

ε = carbon combustion efficiency

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Table 1 - Coal ranks and particle size ranges

Coal ranks		Size fractions mm	
B.	Medium-volatile bituminous	1	12.7 -25.4
C.	High-volatile bituminous B	2	4.76-12.7
D.	Mixed bituminous	3	3.36- 4.76
E.	Lignite	4	0.84- 3.36
G.	High-volatile bituminous C	5	0.60- 0.84

Table 2 - Analysis of coal samples

		Proximate analysis				Ultimate analysis	
Coal	Fractions	Moisture	Ash	Volatile	Fixed carbon	Carbon*	FSI
B	1	1.70	4.45	21.73	72.12	83.39	1/2
	2	1.94	7.35	22.02	68.69	79.81	1/2
	3	2.31	6.48	23.84	67.37	79.72	1/2
	4	2.75	6.95	24.60	65.70	78.99	1/2
	5	2.98	8.35	24.99	63.68	76.69	N/A
C	1	1.98	7.32	36.84	53.86	72.00	1
	2	1.88	9.13	34.50	54.49	68.93	1/2
	3	2.10	12.38	33.30	52.22	66.07	1/2
	4	1.88	11.43	34.09	52.60	67.28	1/2
	5	2.06	17.41	32.29	48.24	63.16	1/2
D	1	1.26	12.35	35.12	51.27	72.94	5
	2	1.62	8.59	35.63	54.16	75.03	6 1/2
	3	1.89	9.89	35.11	53.11	72.45	6
	4	2.36	10.31	34.77	52.56	71.68	5 1/2
	5	3.31	14.53	33.79	48.37	65.22	1
E	1	12.73	4.81	36.57	45.89	66.82	
	2	13.19	12.69	34.67	39.45	59.90	
	3	10.35	15.52	34.22	39.91	57.89	
	4	9.82	15.18	34.75	40.25	58.38	
	5	8.98	19.06	32.25	39.71	56.53	
F	1	6.20	4.33	34.34	55.13	73.34	N/A
	2	5.98	11.49	31.66	50.87	67.63	N/A
	3	6.54	9.14	32.48	51.84	69.54	N/A
	4	6.75	8.98	32.56	51.71	69.15	N/A
	5	5.45	10.24	32.89	51.42	67.83	N/A

*Dry base

Table 3 - Measured elutriated carbon loss

Size fractions	Elutriated carbon loss (%)				
	Coals				
	B	C	D	E	G
1	1.36	11.13	-3.33	13.37	5.42
2	4.11	12.25	6.56	15.94	4.16
3	17.22	14.34	13.77	24.01	13.30
4	21.59	28.45	21.33	24.49	14.33
5	22.50	35.90	30.04	22.68	7.84

①- ROTAMETER
②- VIEWPORT - FEEDER
③- FLUIDIZED BED COMBUSTOR
④- CYCLONE
⑤- CONDENSER
⑥- WOOL FILTER
⑦- DRIERITE
⑧- VACUUM PUMP
⑨- MILPORE FILTER
⑩- GAS ANALYSERS
⑪- CALIBRATION GAS

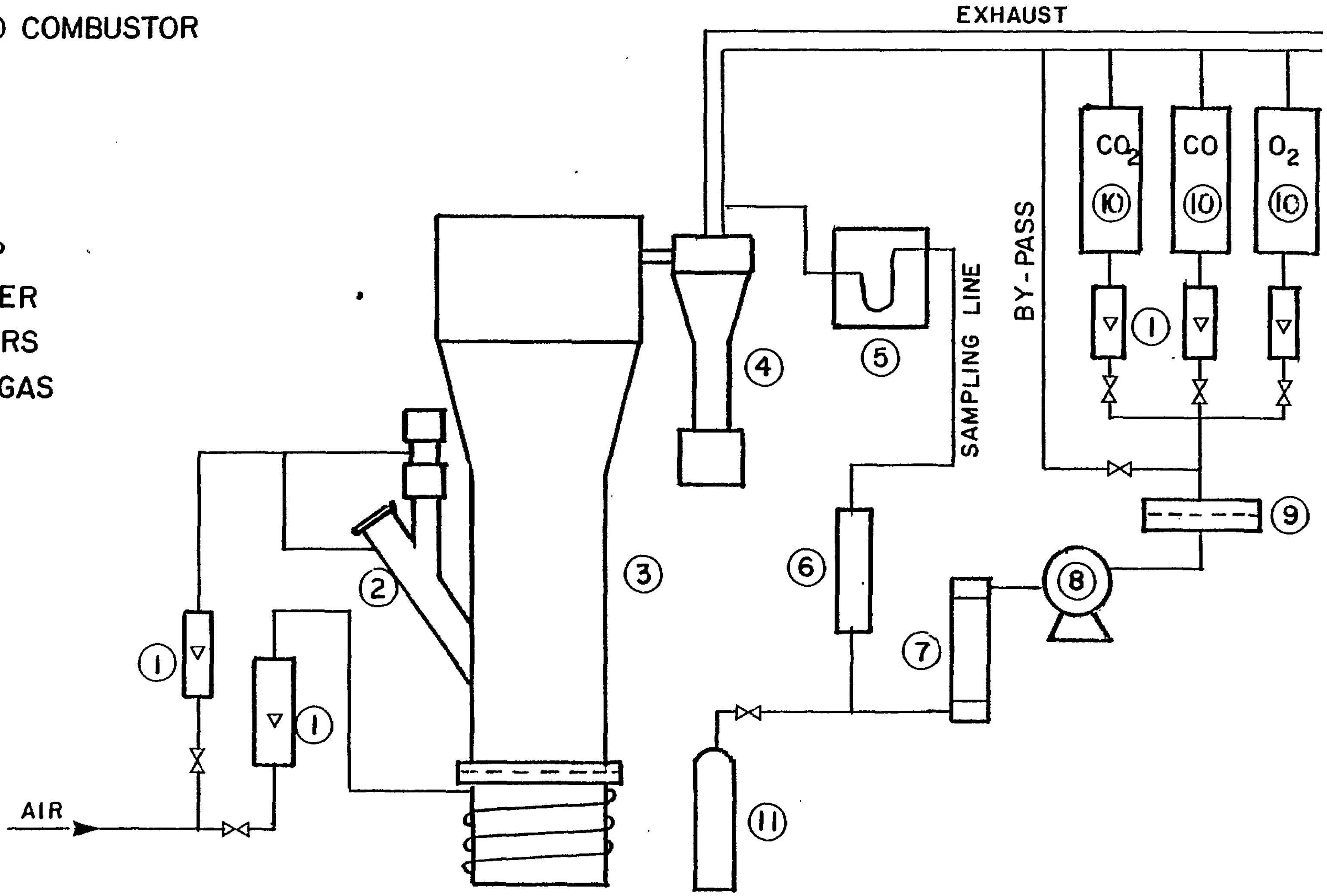

Fig. 1 – Schematic diagram of bench–scale fluidized bed combustor.

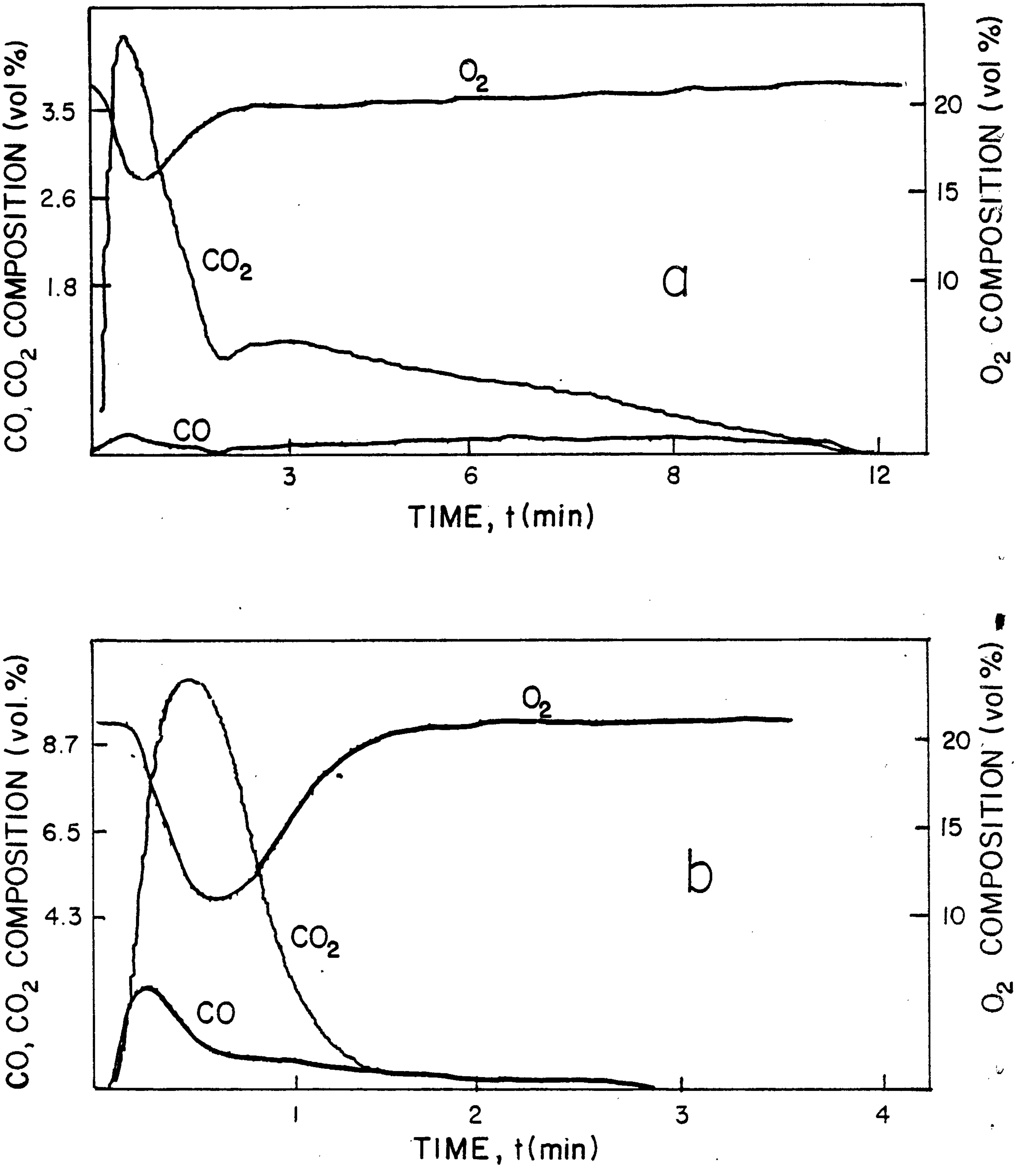

Fig. 2 – Typical flue gas composition

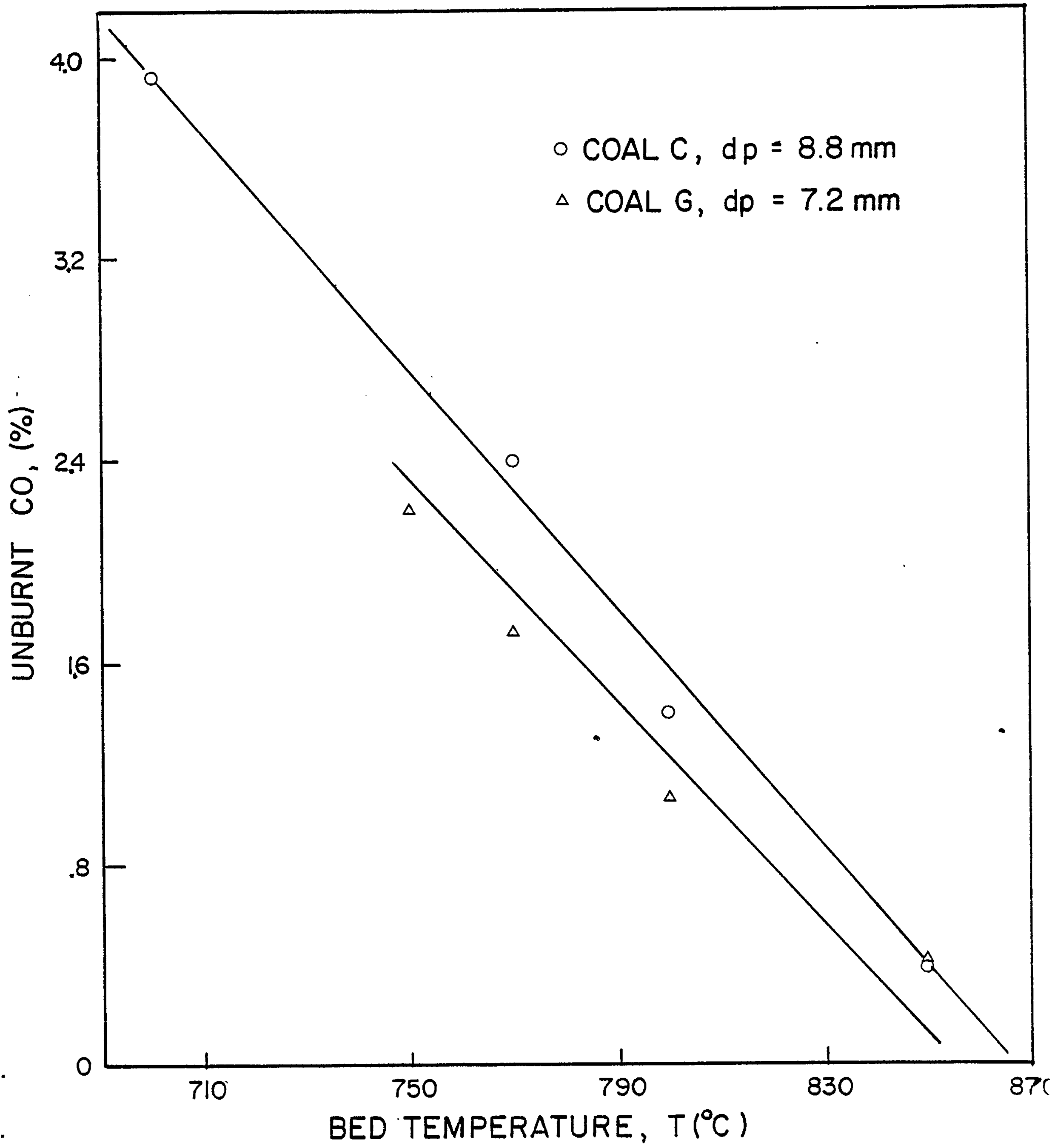

Fig. 3 – Effect of bed temperature on combustion of CO

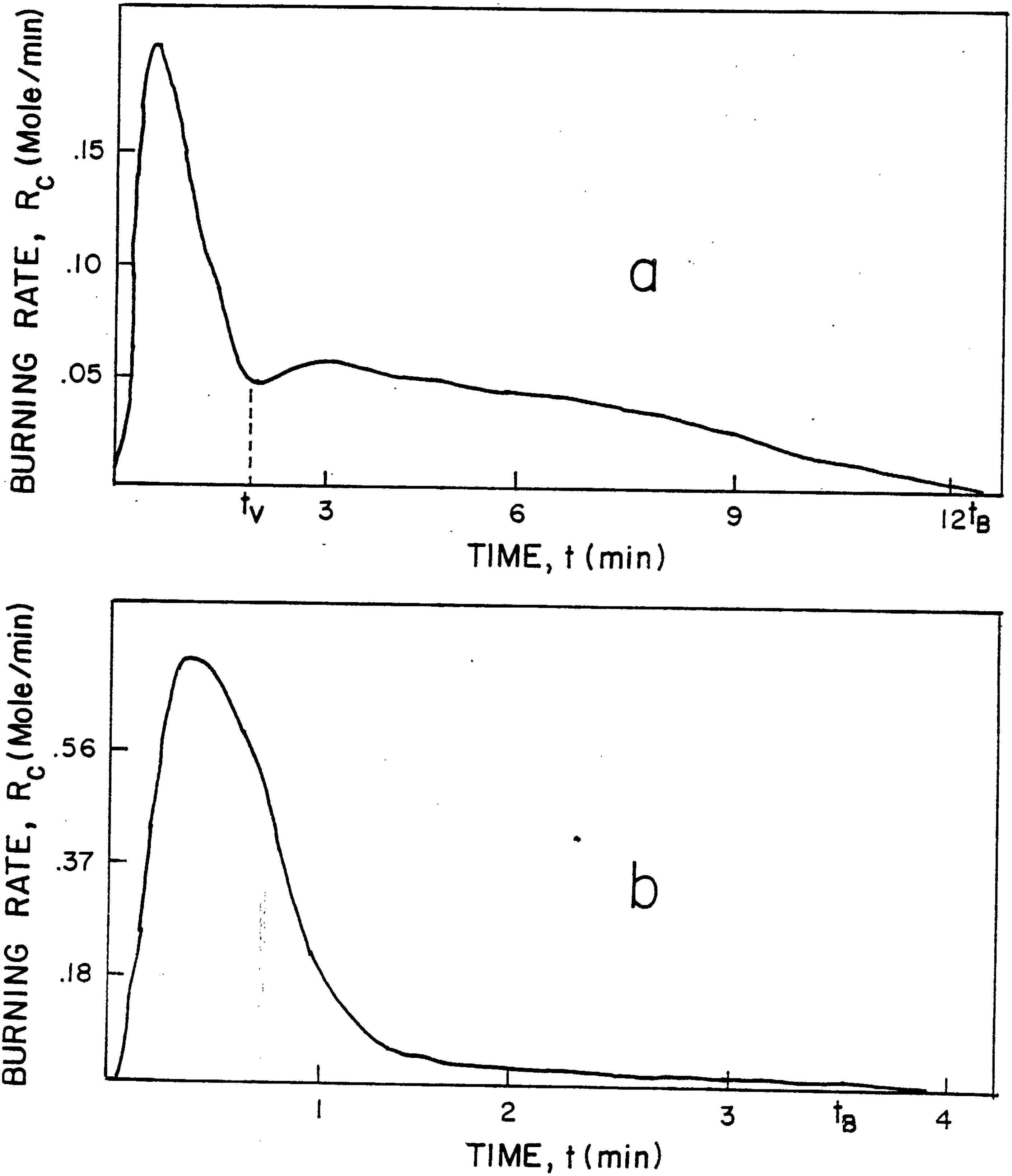

Fig. 4 – Typical carbon burning rate

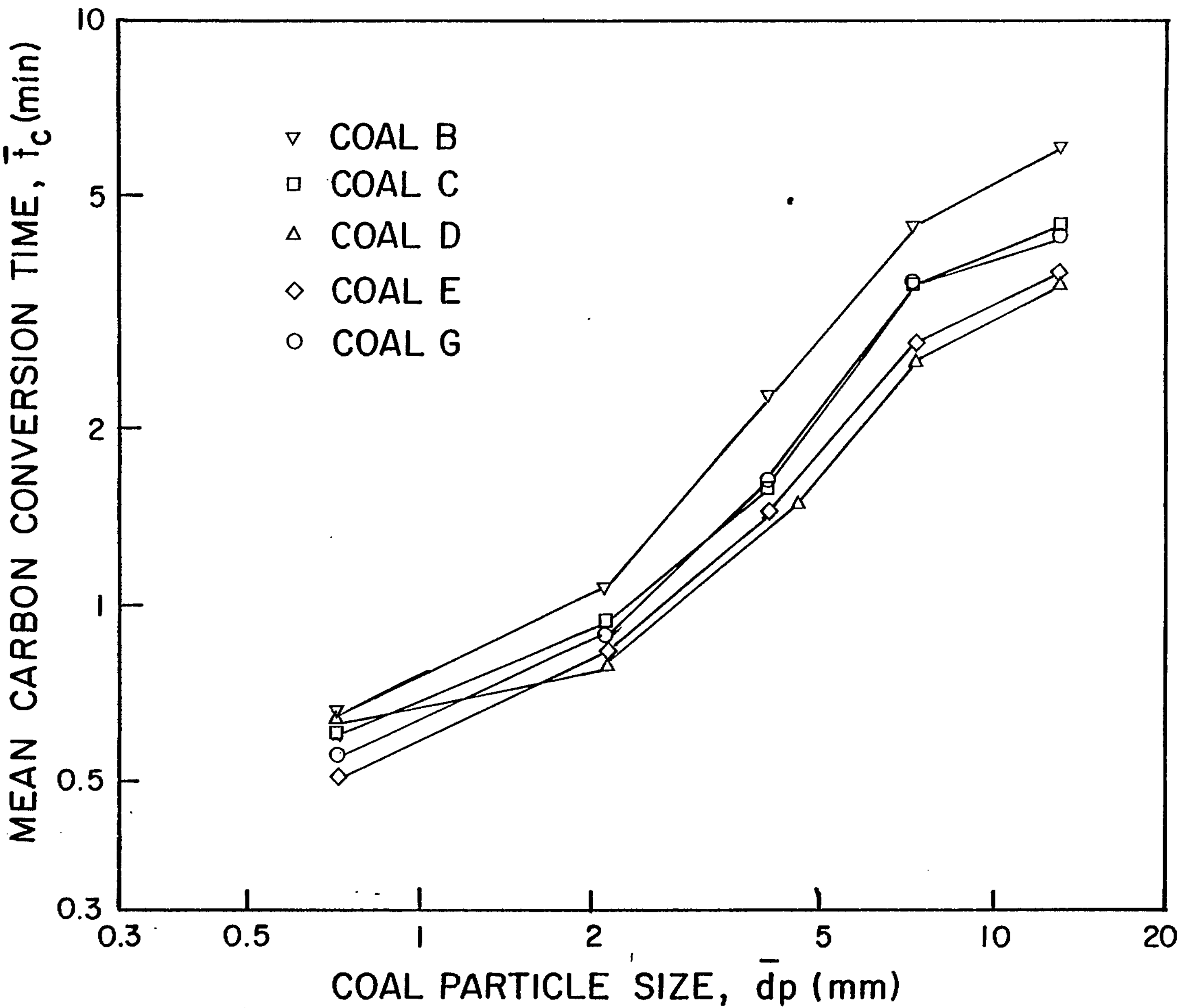

Fig. 5 – Comparison of FBC reactivity of five coals

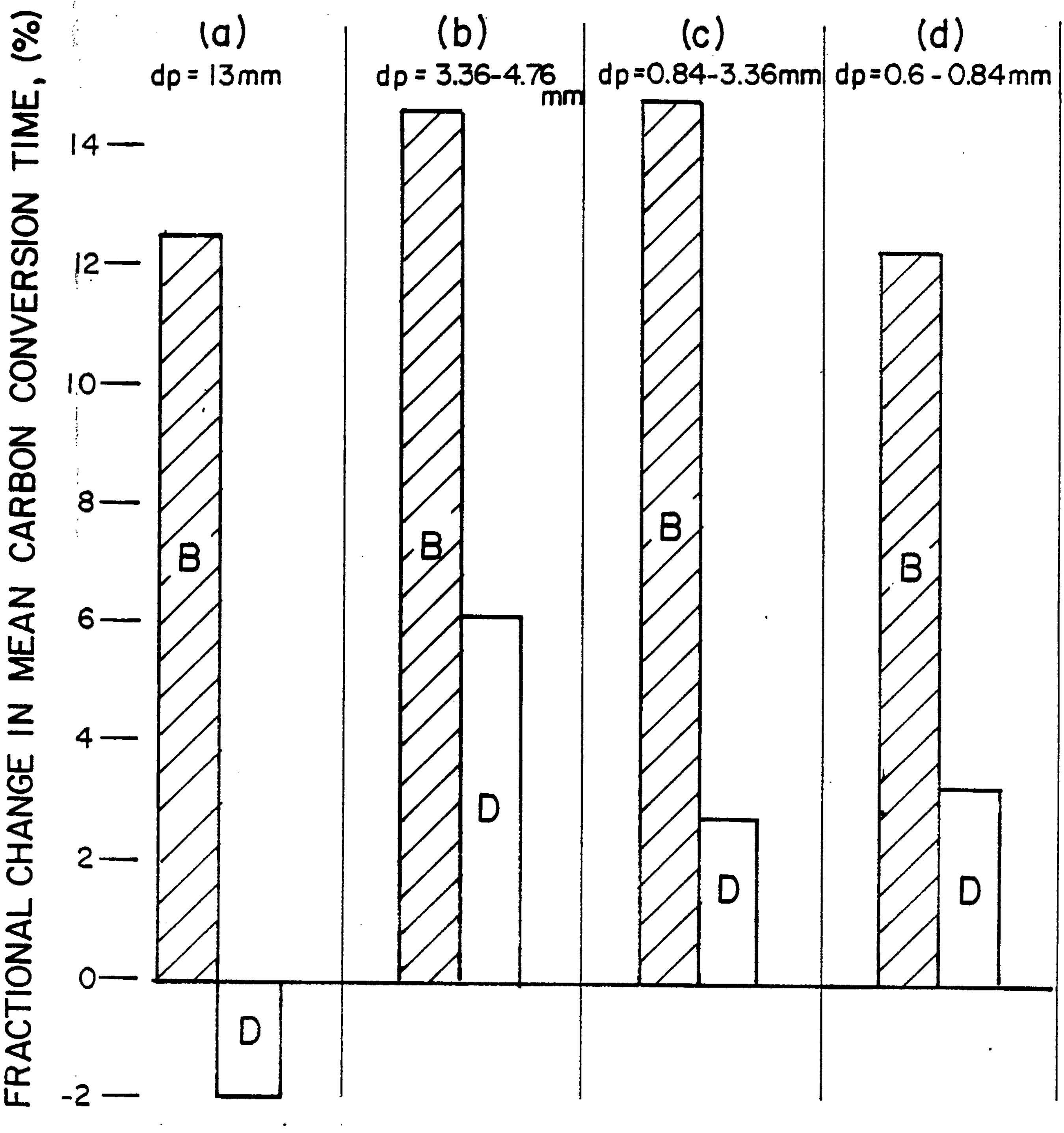

Fig. 6 – Comparison of effect of temperature on FBC reactivity between coal B and coal D

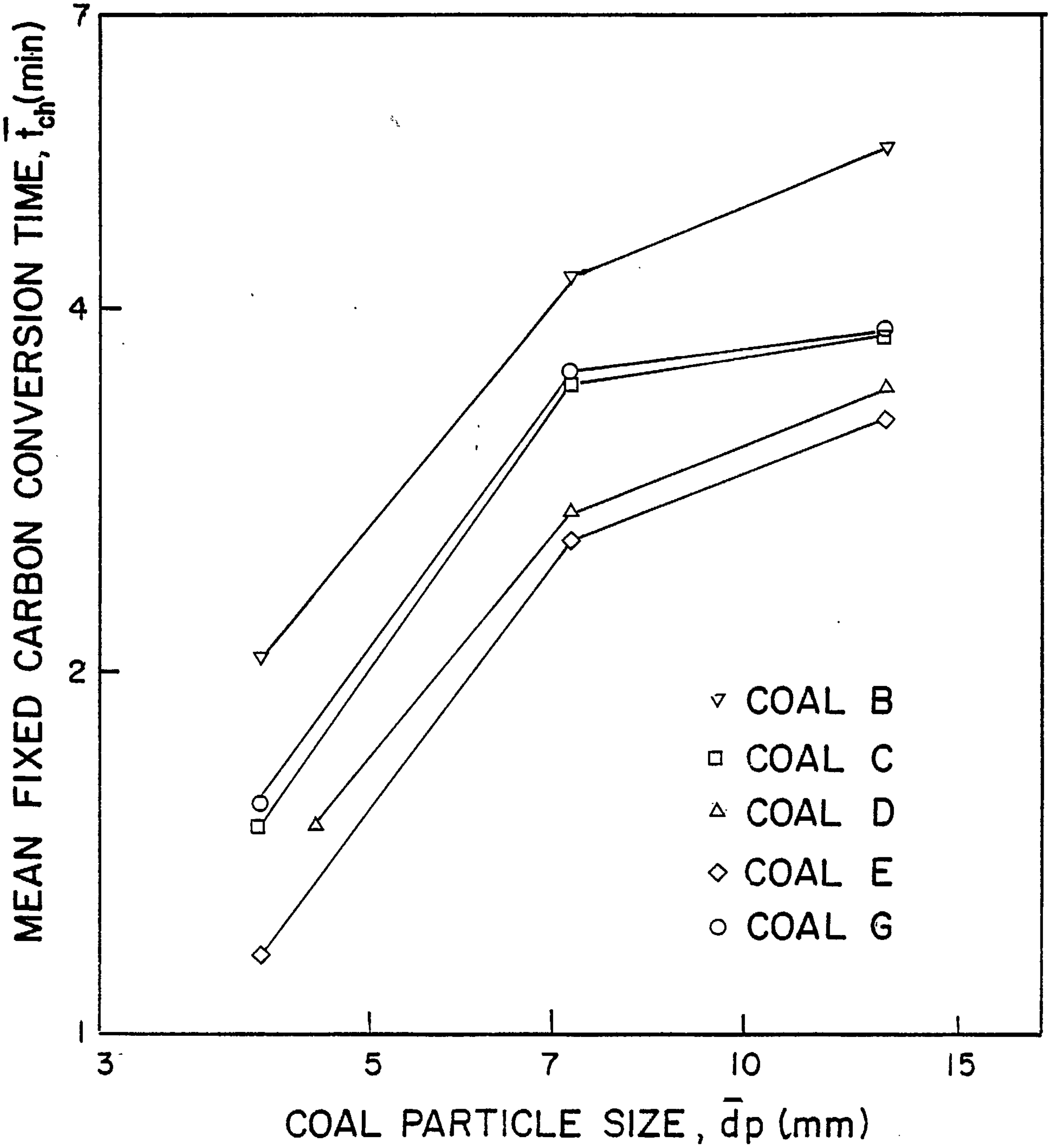

Fig. 7 – Comparison of FBC reactivity of five coal chars

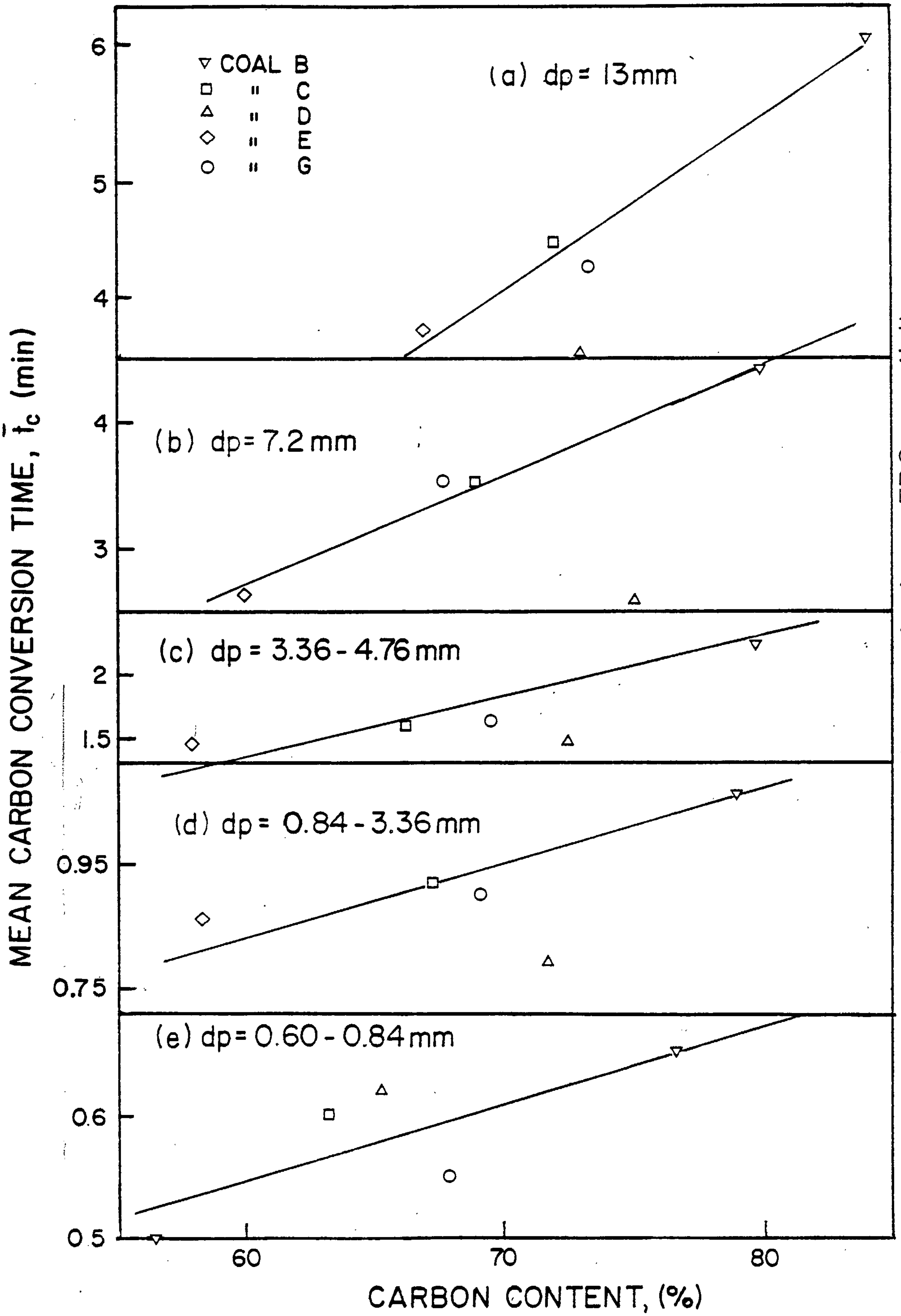

Fig. 8 – Effect of carbon content on FBC reactivity