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Chin, W.K.

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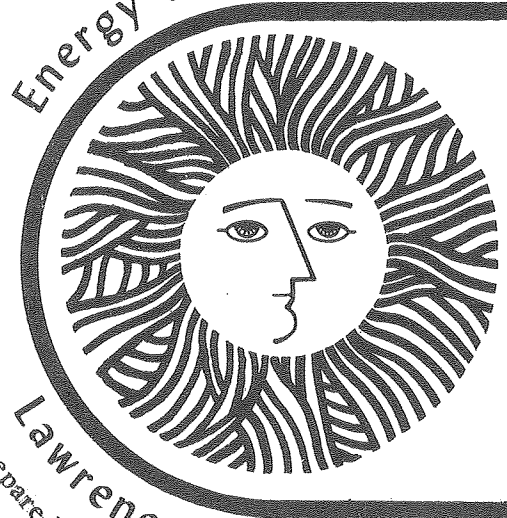
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Combustion of Coal in an Opposed Flow Diffusion Burner

Energy and Environment Division



W.K. Chin
R.F. Sawyer

Department of Mechanical Engineering
University of California
Berkeley, California 94720

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Lawrence Berkeley Laboratory University of California/Berkeley
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ABSTRACT

The utility of the opposed flow diffusion flame (OFDF) apparatus for the study of the steady state combustion of gaseous, liquid, and polymer fuels has been recognized and utilized by a number of researchers. We have employed this configuration to observe the steady state diffusion flame combustion of pressed pulverized coal and graphite in an opposed flow of an oxygen/nitrogen mixture.

Initial efforts have focused upon the pressing of pulverized coal into cylindrical rods of homogeneous properties, including the effect of binders and water content, the demonstration of the possibility of steady state burning of a fuel with a significant ash production, the determination of sample porosity, the measurement of burning (linear regression) rates, and the investigation of the primary experimental parameters--oxidizer flow velocity and oxygen fraction. Burning rates were observed to increase with oxidizer velocity and oxygen mole fraction.

Because of the well controlled combustion environment and steady state burning which are characteristics of this experimental technique, additional measurements are suggested and are being pursued. These include the determination of the solid and gas phase temperature profiles, extraction of thermal diffusivity data under burning conditions, measurement of gas phase composition profiles, investigation of the relative importance of surface oxidation by oxygen and by carbon dioxide, and the determination of the fate of nitrogen contained in the fuel.

INTRODUCTION

The growing and renewed importance of coal as a primary energy source is resulting from a depletion of petroleum and natural gas resources. Past studies of the combustion of coal, carbon, char, coke, and other coal derived or related fuels have been primarily concerned with the observation or prediction of the behavior of these fuels in practical combustion systems. Most of the laboratory experimental efforts have been upon determination of the rates of pyrolysis and combustion of coals and chars and how these are affected by fuel properties such as composition, rank, particle size, heat of combustion, porosity, and other physical and chemical characteristics. Several recent reviews, Essenhigh (1976), Beér (1976), Hardesty (1976), and Lenzer and Laurendeau (1976) summarize information on the gasification and combustion of coal with an appropriate emphasis on pulverized coal since the greatest fraction of coal which undergoes direct combustion is of this form.

A variety of experimental laboratory configurations, including model furnaces, flat flame burners, flow reactors, shock tubes, single particle burners, and, no doubt, others have been employed to observe the combustion of coal. The utility of the opposed flow diffusion flame (OFDF) apparatus for the study of the combustion of gaseous, liquid, and polymer fuels has been demonstrated by a number of researchers: Blazowski, et al. (1973), Evans and Emmons (1977), Holve and Sawyer (1974), Richard, et al. (1974), Seshadri and Williams (1977), T'ien, et al. (1976), and Pandya and Weinberg (1965). We have employed this configuration, Figure 1, to observe the steady state combustion of graphite and of pressed pulverized coal in the opposed flow and oxygen/

nitrogen mixture. The advantages of this geometry lie primarily in the ability to observe the combustion of coal and coal derived fuels in a particularly well controlled, steady state environment. Unlike most other experimental methods, the technique appears to be suitable for the study of a number of coal derived or coal related fuels such as coal, pressed pulverized coal, char, coke, solvent refined coal, and coal liquids--thereby providing a means of comparing the combustion of these fuels under comparable combustion conditions. The limitations of this technique lie in its failure to simulate the rapid heating rates under which pulverized coal usually is burned, to provide a radiation environment similar to furnace combustion, and to allow the direct observation of the combustion of individual particles. With full recognition of these limitations, we have sought to exploit the unique advantages of the OFDF geometry.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the opposed flow diffusion flame apparatus as used for the study of coal and coal derived fuels is shown in Figure 2. The fuel holder and oxidizer nozzle are contained in a 10 cm diameter pyrex cross to eliminate external disturbances to the flame, to aid in the collection of combustion product gases, and to allow operation at below atmospheric pressure if desired. One side of the cross serves as a viewing port and the other provides access for temperature and gas sampling probes. The oxidizer enters through the top flange and the fuel feed mechanism through the lower flange.

The oxidizer flow, consisting of nitrogen and oxygen metered through calibrated rotometers, enters through a pipe filled with 3.0 mm steel balls followed by a nozzle screen to ensure a flow of uniform velocity

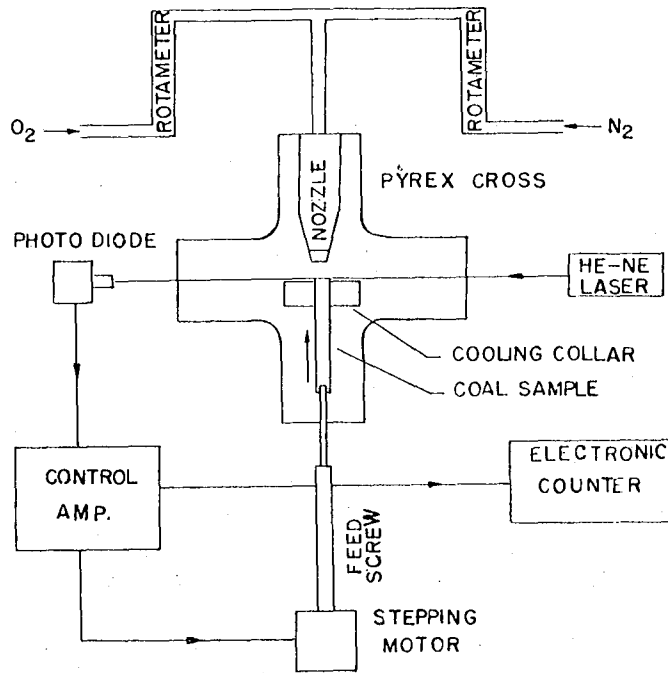


Figure 2. Opposed flow diffusion flame apparatus for the study of the combustion of coal and coal derived fuels.

and composition. A portable torch is used to ignite the fuel sample. Once ignition takes place, the torch is removed and steady state burning is established within several minutes.

The sample feed system has been designed to provide for the accurate placement and determination of the location (within $\pm 10 \mu\text{m}$) of the fuel surface. A laser beam and photo diode detector are used to sense the burning fuel surface, providing a signal to a stepping motor which automatically positions the fuel rod. The linear regression rate is found by an electronic counter which reports the number of pulses to the stepping motor over a selected time interval. Data can be recorded and presented either as accumulated counts (total linear regression) as a function of time or the average regression rate for a selected time interval as a function of time. The steady state character of the combustion can be

established either by the linearity of the former or constancy of the latter. The presently reported burning rates are determined from a best linear fit to the position--time data.

Both the fuel and the oxidizer were at a laboratory ambient temperature, approximately 20 C, and all experiments reported were conducted at atmospheric pressure. The geometry of the experiment is such that there is little radiant heat transfer from high temperature product gases or the combustion environment to the burning fuel. Rather, there is substantial radiant loss from the burning fuel surface to the surroundings. Because of this heat loss, it is not possible to burn coal samples in air, but oxygen enrichment is required to sustain combustion. The limiting oxygen index for the burning of coal in this geometry is greater than .21 with the determination of the precise level difficult because of poorly defined extinction and ignition conditions.

PREPARATION OF FUEL SAMPLES

Commercial electrode graphite rods were burned to establish the suitability of the opposed flow diffusion flame method to the study of solid, high carbon content fuels. For initial studies of coal combustion, pressed pulverized coal was selected because of the chemical and physical homogeneity which such a material exhibits, especially in contrast to coal itself which is highly anisotropic and presents difficulty in insuring constancy of chemical composition from sample to sample.

Coal samples used in our experiments were prepared from Pittsburgh seam pulverized coal, screened through a 35 mesh sieve (417 μm hole size). Properties of this coal are reported in Table 1. Rods 12.7 mm in diameter

TABLE 1. Pittsburgh seam coal properties, Grosshandler (1976)

Chemical Composition, Weight %:	C, 76.72 %	
	H, 5.12 %	
	N, 1.45 %	
	S, 1.16 %	
	Ash, 6.05 %	
Estimated Size Distribution, Weight %:	> 85 μm ,	1.3 %
	74 to 85 μm ,	.8 %
	43 to 74 μm ,	6.6 %
	30 to 43 μm ,	5.3 %
	20 to 30 μm ,	18.0 %
	10 to 20 μm ,	42.0 %
	< 10 μm ,	26.0 %
Enthalpy of Reaction with Air:	31.4 kJ/g	

and about 60 mm in length were pressed in a plunger and die apparatus, Figures 3a and 3b, at a pressure of about 47 MPa. The cone shaped mandrel has been used to prepare samples with embedded fine wire thermocouples. The fragility of the samples created problems in mounting the sample onto the feeding rod, embedding thermocouples, and generally in the handling of the samples. As a consequence, a binder was used to produce more durable samples. Following the practice used in the preparation of commercial coal and charcoal briquettes, a starch was employed. We used corn starch, a polysaccharide, high molecular weight polymer of glucose. A coal slurry consisting of 80% pulverized coal, 15.3% water, and 4.7% corn starch at 50 C was found suitable for the preparation of durable pressed-pulverized coal samples. Water content of the samples was then varied, following pressing, through dessication.

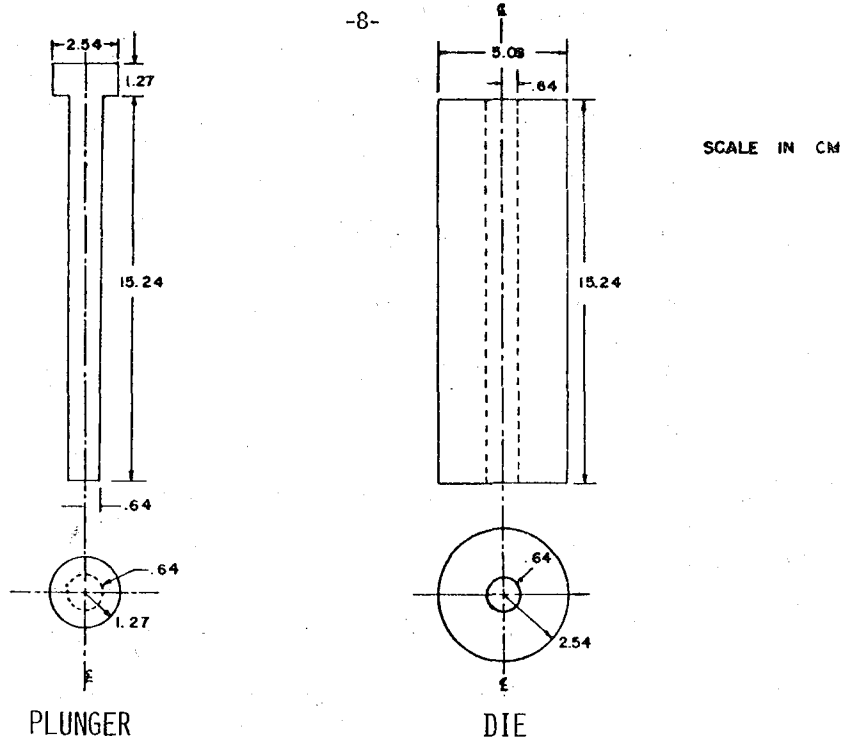


Figure 3a. Plunger and die for the preparation of pressed pulverized coal samples.

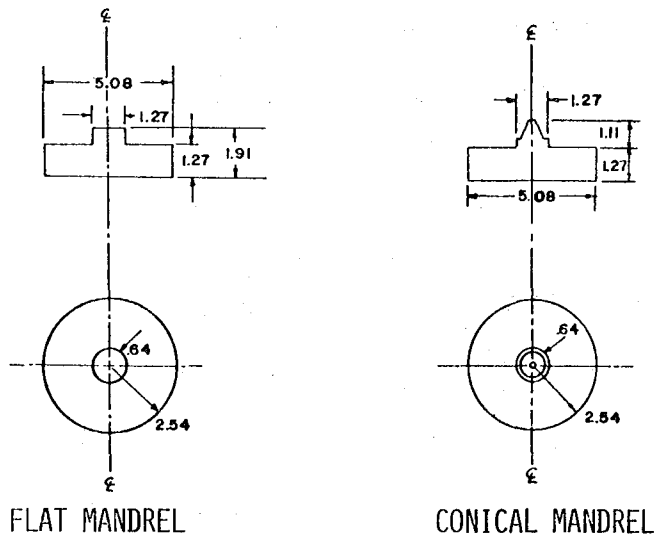


Figure 3b. Mandrels for the preparation of flat and recessed sample ends.

VOID AND PORE VOLUME MEASUREMENT

A 400 MPa porosimeter capable of measuring pore sizes from 170 down to .003 μm diameter was used to measure the void volume and pore size distribution of the pressed pulverized coal samples. A mercury intrusion technique was used to measure the void and pore volume of the sample. Two independent pressurization systems were employed. An evacuation system was used for effective void and pore diameters between 170 and 12 μm and a 400 MPa pressurization system for pore diameters from 12 down to .003 μm . The pressed pulverized coal was placed in the sample bulb of a penetrometer which was then evacuated to a pressure of 50 μm of mercury and the sample allowed to outgas. Mercury was then allowed to enter the sample and the intrusion volume determined as a function of pressure, up to a pressure of one atmosphere. The diameter of the smallest pore penetrated by the mercury at each test pressure is inversely proportional to the absolute pressure of the mercury at the surface of the pore and given by the Washburn equation

$$d = \frac{-4\sigma \cos \theta}{P}$$

where σ is the surface tension of mercury, θ is the contact angle between mercury and the pore wall, and P is the pressure. The relation between the pore diameter and mercury pressure then becomes

$$d = \frac{1222.4}{P}$$

where d is the pore diameter in μm and P is the pressure in kPa.

After atmospheric pressure is reached, the penetrometer is transferred to the porosimeter pressure vessel which utilizes hydraulic

fluid to further pressurize the mercury, forcing it into the sample void spaces and pores. The mercury volume change is detected by a capacitance change.

An intrusion volume measurement is shown in Figure 4. The steep rise in intrusion volume at about 70 kPa is due to the void volume and indicates a void size in the range of about 10 to 30 μm which is consistent with the size distribution of the coal particles. Taking the void volume to be $.27 \text{ cm}^3/\text{gm}$ from this measurement, the coal density (solid coal before pulverization) may be estimated from the measured density of the pressed pulverized coal, 0.92 gm/cc . The resulting value for the coal density of 1.22 gm/cc is in agreement with the reported value of $1.2 - 1.4 \text{ gm/cc}$ (Wilson, 1950). The change in intrusion volume at greater than about 10 MPa indicates a coal pore size of less than about $0.1 \mu\text{m}$ which is also consistent with the reported values (Gan, et al., 1972).

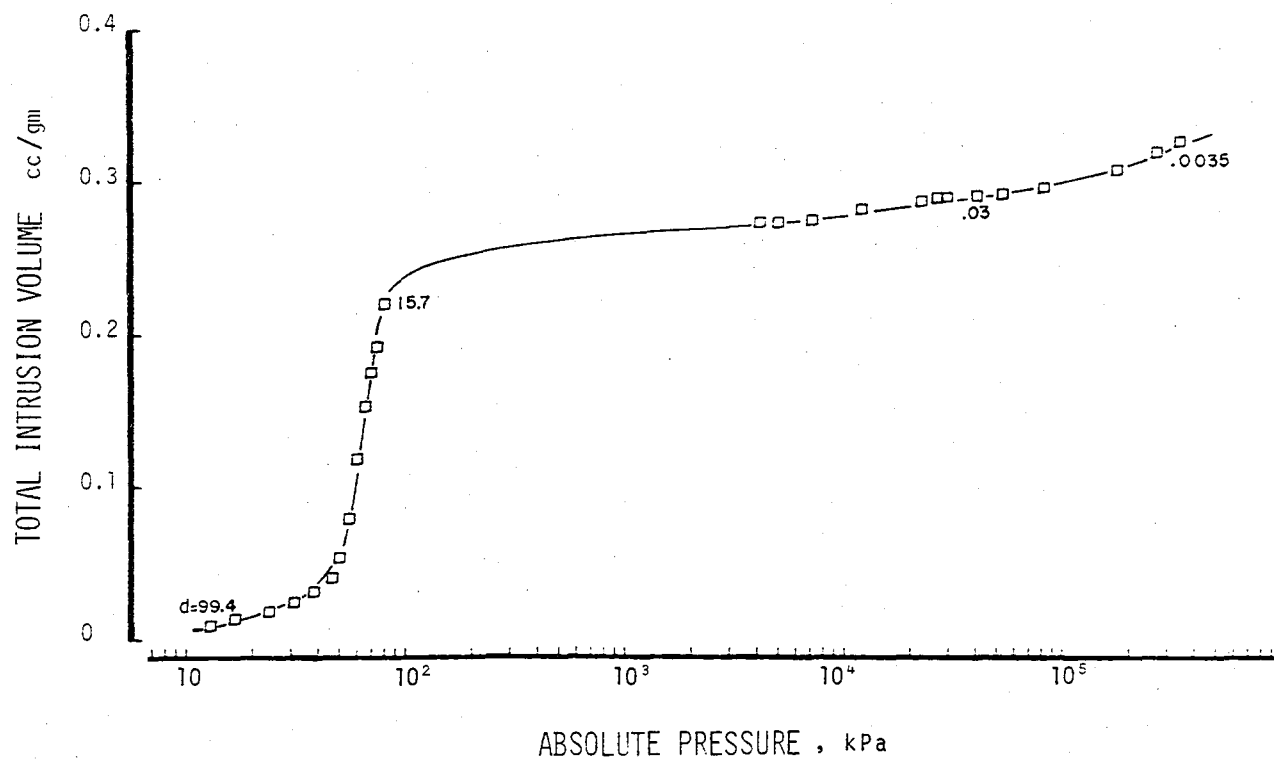


Figure 4. Mercury porosimeter measurements of pressed pulverized coal sample.
 d = diameter of void or pore volume in μm

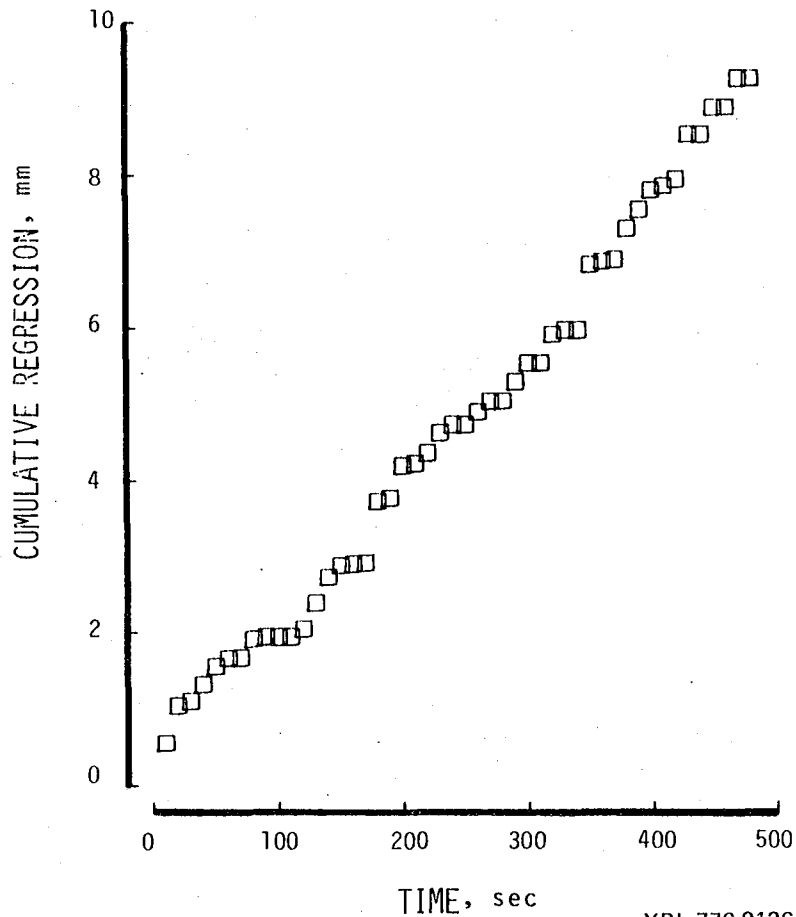
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BURNING RATE RESULTS

Burning rates were measured as linear regression rates for several sample compositions and under a range of oxidizer flow rates and oxygen mole fractions. A typical record of the regression rate history of a pressed-pulverized coal sample is shown in Figure 5. The irregularities in the regression are caused by the build up and removal of an ash layer which is the result of the approximately 6% ash content of the Pittsburgh seam coal. As the ash layer begins to develop on the burning surface, the apparent burning rate falls as the feedback control mechanism cannot distinguish between the ash and unburned fuel. When the ash is removed, generally by the blowing action of the oxidizer flow, the sample is then advanced to bring the fuel surface up to the set point for the fuel location, producing an apparently oscillatory output in the regression record. Averaged over these unsteady ash removal processes, however, the burning rate appears constant with time.

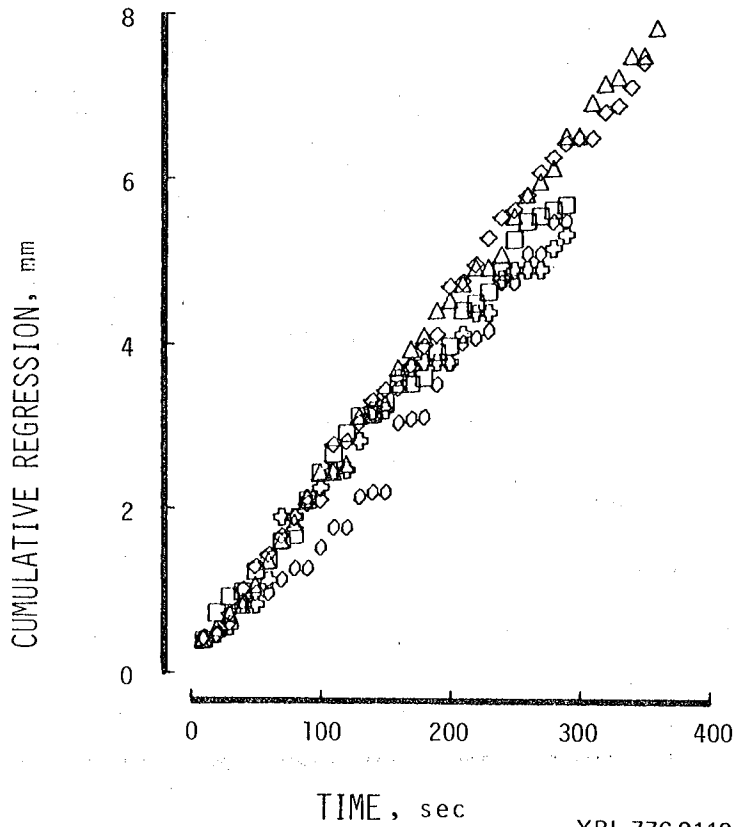
The reproducibility of the sample preparation and burning rate measurements is shown in Figure 6. Five different samples, all with a density of 0.92 g/cm^3 , oxidizer composition (30% O_2 in N_2), and oxidizer flow velocity of 380 cm/sec show similar burning rates. The regression rates found by best fit are within 10 percent. The initial times are arbitrarily selected so that the data follow any transients which are associated with the ignition process and establishment of steady state burning.

The effect of sample water content was studied through varying the amount of moisture removed following the pressing of the pulverized coal samples. As shown in Figure 7, increasing water content leads to



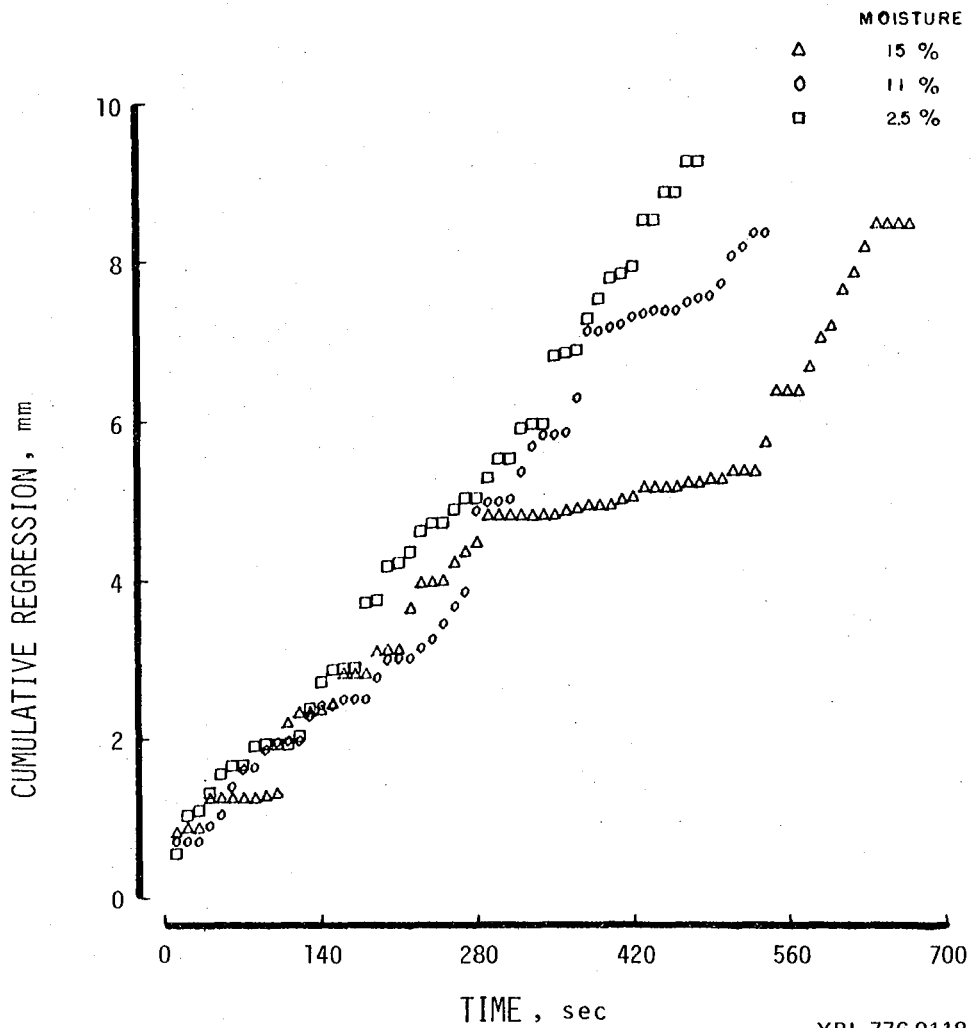
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Figure 5. Experimental regression curve for pressed pulverized coal burning in a mixture of .30 O_2 + .70 N_2 ; oxidizer blowing velocity, 380 cm/sec; sample density, 0.92 gm/cm³.



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Figure 6. Experimental regression curve for pressed pulverized coal samples in a mixture of .30 O₂ + .70 N₂; oxidizer blowing velocity, 380 cm/sec; sample density, 0.92 gm/cm³.



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Figure 7. Effect of water concentration on the burning characteristics of pressed pulverized coal in a mixture of .30 O₂ + .70 N₂; oxidizer blowing velocity, 380 cm/sec; average sample density, 0.92 gm/cm³.

irregular burning associated with highly irregular ash removal, in particular, the incidence of events of substantial ash build-up. The burning rate, as indicated by the slope of the regression curve outside of the period of ash build-up, does not, however, appear to be strongly affected by the water content of the sample. During the burning of the sample with water content of 15 percent by mass, which is the amount used with the binder for pressing the sample, it was observed that the circumference of the sample did not burn. Heat loss to the cooling collar could also contribute to this effect.

The effect of oxidizer oxygen concentration was investigated by burning samples under conditions of constant oxidizer velocity of 380 cm/sec but with oxygen mole fractions varying from 27% (approximately the lowest oxygen concentration at which steady combustion could be sustained) to 40%. The burning rates for five cases are summarized in Table 2 and

TABLE 2. Summary of selected regression rate data.

Sample	Density (gm/cc)	Oxidizer velocity (m/sec)	$\frac{O_2}{O_2 + N_2}$ (-)	Burning rate (gm/sec)	Regression rate (mm/sec)
B-3-25	.92	3.8	.27	.0014	0.012
B-3-20	.92	3.8	.30	.0022	0.019
B-3-30	.92	3.8	.32	.0026	0.022
B-3-22	.92	3.8	.35	.0036	0.030
B-3-24	.92	3.8	.40	.0037	0.032

plotted as a function of oxygen mole fraction in Figure 8. Regression rates are seen to increase with oxygen concentration in a fashion

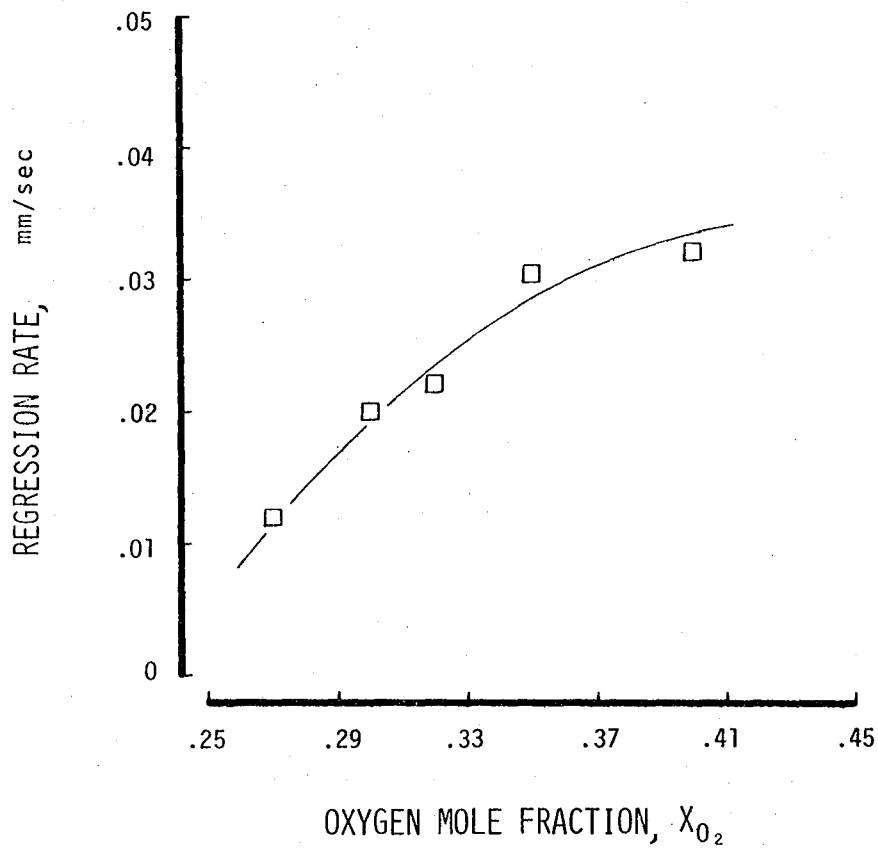


Figure 8. Dependence of regression rate of pressed pulverized coal on oxygen mole fraction; constant oxidizer velocity, 380 cm/sec.

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suggesting a power law dependence. These same data are shown in a log-log plot in Figure 9. The empirical regression rate dependence on oxygen mole fraction has the following form

$$\dot{r} = 0.098 (X_{O_2} - .27)^{.74} + .012$$

where the linear regression rate, \dot{r} , is in mm/sec. This dependence upon oxygen concentration is within the range of .5 to 1 reported in most investigations, Essenhigh (1976).

Burning rates determined in OFDF measurements for a number of solid fuels are summarized in Table 3. These measurements were made in 100%

TABLE 3. Burning rate data for selected solid fuels.

Material	Density (gm/cm ³)	O ₂ Velocity (cm/sec)	Burning Rate (gm/sec)	Burning Rate (mm/sec)
Polymethyl methacrylate	1.176	253	.0137	.0922
Maple Wood	0.731	253	.0059	.0640
Graphite I	1.528	589	.0083	.0427
Graphite II	1.334	479	.0047	.0279
Coal C-2 ⁽¹⁾	1.097	253	.0047	.0340
Coal B-4-1 ⁽²⁾	0.950	253	.0040	.0330
Coal B-3-2 ⁽³⁾	0.902	253	.0043	.0279

- (1) Pressed pulverized coal, no binder
- (2) Pressed pulverized coal, with binder, unsieved
- (3) Pressed pulverized coal, with binder, sieved

oxygen flows but with differing flow velocities so that direct comparison is not possible in all cases.

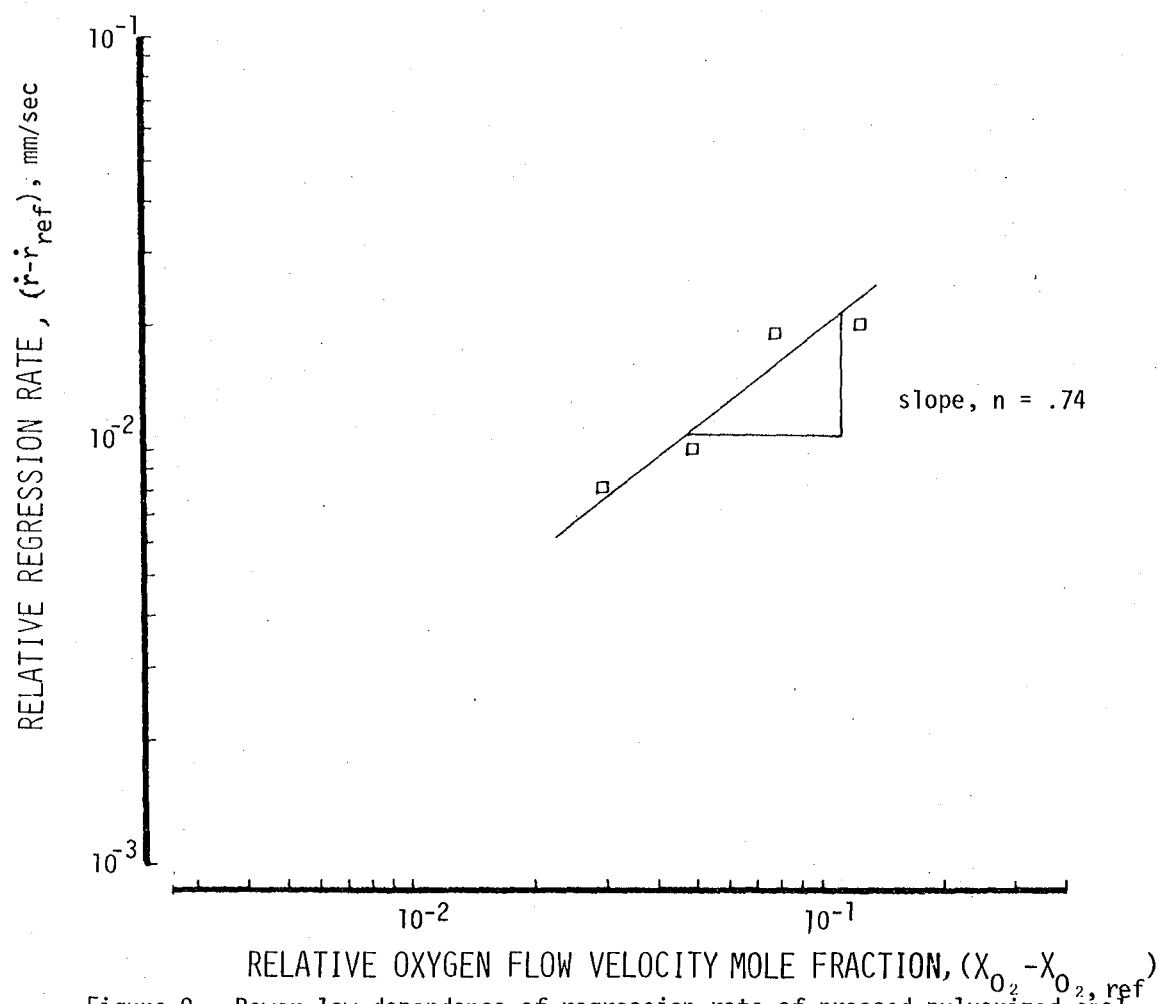


Figure 9. Power law dependence of regression rate of pressed pulverized coal on oxygen concentration; constant oxidizer velocity, 380 cm/sec.
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SUMMARY AND CONCLUSIONS

The experimental program has demonstrated the suitability of the opposed flow diffusion flame technique to the study of the combustion of graphite and pressed pulverized coal samples, even in cases where there is a substantial ash fraction, 6 percent. Porosimeter measurements indicate void and pore characteristics in the pressed samples which are consistent with the reported properties of the pulverized coal. The pressed samples can be burned under steady state conditions of up to about ten minutes and burning rate data obtained. In a limited number of experiments, the linear regression rate showed a .74 power dependence upon the oxygen concentration in oxidizer flow. High sample water contents lead to highly irregular ash removal and discontinuities in the burning rate curves but appear to have little effect on the steady state burning rate. The potential of the method for the comparative investigation of the combustion characteristics of coal and coal derived fuels is considered to be high.

ACKNOWLEDGEMENTS

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