AN EXAMINATION OF BURNING PROFILES AS A TOOL TO PREDICT THE COMBUSTION BEHAVIOR OF COALS

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Introduction

Thermal analytical techniques such as thermogravimetric analyzer (TGA) have been used extensively in characterizing the thermal behavior of coals. Intrinsic reactivity (expressed as instantaneous, average and time required for 50% burnoff (τ_{50})), volatiles release profiles and burning profiles are common parameters used to predict combustion behavior in a large combustion system. The burning profile provides information on the combustion rate including intensity of reaction, heat release rate and residence time requirements for a fuel compared to those of a fuel with known combustion characteristics. The technique for determining the burning profile was developed by Babcock and Wilcox as a method for evaluating fuels to select the optimum boiler design (Wagoner and Duzy, 1967). The technique has been modified by others (Cumming, 1984; Cumming and McLaughlin, 1982; Morgan et al., 1986, 1987; Smith et al., 1981) to characterize the combustion behavior of coals in a laboratory. However, information on the validity of these profiles to industrial scale and utility boilers is scarce.

Penn State Energy and Fuels Research center evaluated combustion behavior of coals in various devices ranging from drop tube reactor to an industrial scale boiler. This paper summarizes the observations, and discusses the applicability of the data from the profiles to predict the combustion behavior.

What is a Burning Profile ?

A burning profile is a plot of the rate at which a solid fuel sample changes weight as a function of temperature, when heated at a constant rate. Cumming and McLaughlin (1982) used four characteristic temperatures to interpret a burning profile; 1) the first initiation temperature where the weight first begins to fall (IT_{VM}); 2) the second initiation temperature where the rate of weight loss accelerates due to the onset of combustion of char (IT_{FC}); 3) the peak temperature (PT) where the rate of weight loss is a maximum; and 4) the burnout temperature, where the weight becomes constant at the completion of burning (BT). Cumming (1984) later proposed in lieu of the above four characteristic temperatures, a weighted mean apparent activation energy value which correlated well with the PT. These characteristic temperatures as proposed by Cunning and McLaughlin (1982) have been used with minor modifications by Morgan et. al. (1986, 1987) to interpret burning profiles.

Literature Review

Wagoner and Winegartner (1973) reported a successful combustion evaluation of fluid coke from a California crude and a delayed coke derived from a Louisiana crude oil with respect to a reference combustion profile of Pocahontas coal. These profiles were reported to predict the performance of these fuels in an industrial boiler. Smith et al. (1981) later evaluated the relative ease of combustion of sixty-six coals ranging in rank from lignite to low-volatile bituminous and with low mineral matter contents. The activation energies obtained varied from 4 KJ mol $^{-1}$ in the high temperature, diffusion controlled zone to 290 KJ mol $^{-1}$ in the chemical reaction controlled, low-temperature zone.

Morgan et al.(1986) correlated the BTs from the burning profiles to predict burnout values based on a model that uses data on oxidation rates of chars prepared in an entrained flow reactor and coal properties. Nine coals were ranked based on their performance in a pilot scale pulverized coal combustor and the ranking correlated well with the characteristic temperatures from the burning profiles of the coals. Superior burnout has been reported with coals having low burnout temperatures.

Wagoner and Winegartner (1973) reported that the Pocahontas coal with a volatile matter content of 14-16.5% and a Bureau of Mines char with a 5% volatile matter should have identical combustion characteristics based on their burning profiles. But, Demeter et al. (1973) found that in a 500 lb/hr experimental coal combustor the Pocahontas coal burnt with out any auxiliary fuel or preheat of the primary air whereas the Bureau of Mines char needed preheat or auxiliary fuel to burn successfully .

Experimental

In this study combustion behavior of coals as evaluated in a drop tube reactor, a research boiler generating 1,000 lb/h steam and a 15,000 lb/h (steam) industrial scale demonstration boiler is reported. For coals tested in these devices, burning profiles were obtained in a Perkin Elmer TGA.

The experimental variables in the TGA which were found to affect the rate of burning and hence the burning profile included heating rate, sample weight, shape and material of construction of the sample pan and the heat capacity of the pan. Although the experimental conditions originally employed by Wagoner and Duzy (1967) allow the combustion rate to be limited by the diffusion rate of oxygen, as shown by Smith et al. (1981), and the temperature of the sample may not have been representative of the temperature of the burning fuel, the burning profile data obtained in the TGA seemed to produce consistent results in the evaluation of the relative combustion performance of unknown fuels with different equipment in different laboratories.

The results during optimization of test conditions indicated a good reproducibility of characteristic temperatures (± 1.8°C). The effect of heating was determined using an Upper Freeport seam coal for heating rates of 5, 10, 15, and 20°C min^{-1} and a sample weight of 5 mg. The results are shown in Table 1. It is seen from the results that as the heating rate was increased the characteristic temperatures proportionately increased which did not change the relative ranking of a coal. At higher heating rates some low rank coals ignited and therefore, led to uncontrolled temperature of the sample. Hence, a heating rate of 10°C min^{-1} was used in this study. The effect of sample amount was not as significant as that of heating rate and a sample size of 5 mg was used.

Table 1. Effect of Heating Rate on Characteristic Temperatures

Heating Rate	5°C/min	10°C/min	15°C/min	20°C/min
Initial Temperature (IT)	325.6	337.5	350.0	347.0
Peak Temperature (PT)	494.1	505.1	522.6	618.3
Burnout Temperature (BT)	542.0	616.0	618.3	630.0

The following characteristic temperatures as defined in earlier work (Pisupati et al., 1991 and Pisupati and Scaroni, 1993) were obtained for each sample. The Initial Temperature (IT), is defined as the temperature at which the rate of weight loss exceeded 0.1% min^{-1} after the initial moisture loss peak. The Peak Temperature (PT) is defined as the temperature at which the rate of weight loss was maximum and the Burnout Temperature (BT) is the temperature at which the rate of weight loss decreased to 1.0 % min^{-1}.

Results and Discussion

In an earlier study conducted in the laboratory, a set of five fresh and companion crop coals was used to investigate the influence of natural weathering (in-situ) and low-temperature oxidation on the combustion behavior of the coals. In the study a fresh coal sample was oxidized in the laboratory for 2 hours, and for 72 hours in stagnant air to oxidize the coal to a similar level to that of the naturally weathered crop coal. Combustion behavior of the suite of coals was determined in the laboratory by obtaining burning profiles and the combustion efficiency in a drop tube reactor. The characteristic temperatures were derived from the burning profiles. Figure 1 shows the profiles for the Fort Palmer fresh and crop coals. Analogous profiles were obtained for other samples. The initial negative weight change in the burning profiles is due to the loss of moisture. The second positive peak at around 300°C for the fresh coal samples is attributed to the adsorption of oxygen, and represents a weight gain of about 3%. Adsorption of oxygen by the significantly oxidized crop coals was not apparent and these coals had lower initial temperatures (approximately 20-115°C less) than the corresponding fresh coals. This can be explained as follows. Desorption of the preoxidized oxygen in the crop coals creates unoccupied sites for further oxygen adsorption and subsequent desorption, thereby initiating significant weight loss at much lower temperatures.

For these oxidized coals, it was observed that there were two distinct peaks The lower peak is attributed to the decomposition of the carbon-oxygen complex and to the devolatilization of the coal. The height of this peak for the crop coals was proportional to the degree of oxidation. These profiles indicated that combustion is expected to be complete for the crop coals at lower temperatures than for their companions for otherwise the same operating conditions.

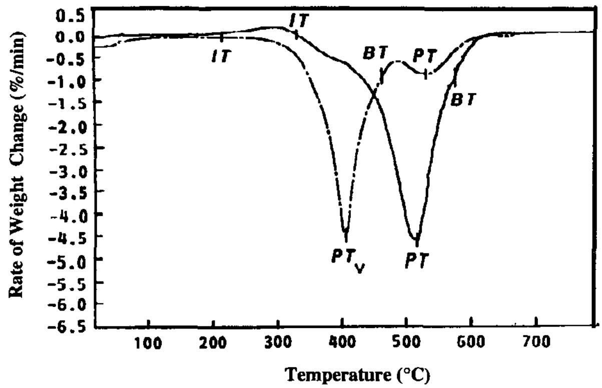

Figure 1. Burning Profiles for the Fort Palmer Fresh (——) and Crop (- - -)Coals

The combustion efficiencies were conducted in a vertical, electrically heated drop tube reactor (DTR). Details of the reactor can be seen elsewhere (Pisupati and Scaroni, 1993). A relatively low combustion temperature of 1,300°C was used to accentuate the differences in combustion efficiencies. A coal feed rate of 0.33 g min^{-1} and a total combustion air of 4 l min^{-1}, which corresponds to an excess air of 25%, was used. The results from the combustion studies in the drop tube reactor were consistent with observations from the burning profiles. Figure 2 shows a correlation between the burning profile data and the combustion efficiency determined in the DTR. The figure indicates that the lower the initial temperature, the higher the combustion efficiency.

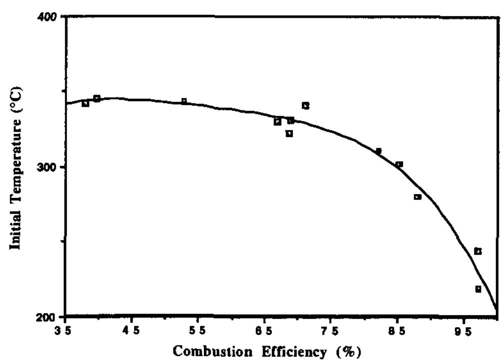

Figure 2. Initial temperatures (IT_{bp}) Obtained from Burning Profiles as a Function of Combustion Efficiency Determined in the DTR.

In another study, combustion behavior of two Pennsylvania bituminous coals, an Indonesian subbitminous coal, and blends of PA and Indonesian coals was determined in a research boiler. Burning profiles were obtained for these coals and blends in the TGA prior to the combustion tests in the boiler. The compositional analysis of the coals is provided in Table 2.

The combustion tests were conducted in a 1,000 lb steam /h water tube research boiler with a maximum thermal input of 2 million Btu/h. The boiler is a standard Cleaver Brooks "A-frame" water tube boiler. The combustion chamber is 3 ft wide, 3 ft high and 7 ft long. To promote evaporation and ignition of difficult-to-burn fuels, a ceramic quarl extends the length of the combustion chamber by two feet. The quarl and the boiler are preheated by burning natural gas prior to introducing of the test fuel until the surface temperature was approximately 900°F. The

Table 2. Proximate Analysis (wt.%, d.b.)

	100% PA	80% PA - 20% Indonesian	50%PA - 50% Indonesian	100% Indonesian	100% Upper Freeport (PA)
Volatile Matter	20.47	25.17	32.74	46.20	31.89
Fixed Carbon	67.19	64.70	60.13	52.14	61.61
Ash	12.34	10.13	7.13	1.66	6.50
Moisture (as-fired)	1.69	7.46	12.73	21.44	7.14
H.H.V.(Btu/lb as fired)	13,680	12,679	11,617	10,098	13,680

preheated quarl acts as a source of radiant heat to help support the flame. Pulverized coal was fed from a two foot diameter hopper to an eductor via a 1.5-inch diameter screw feeder. The pulverized coal was entrained by dense phase transport ($\approx$1 lb of air/lb of coal) into an annular section and then through a swirler. The feed rate of pulverized coal was monitored by load cells. Slowly, the coal firing rate was increased while reducing simultaneously the natural gas rate until the desired load was obtained on coal. A thermal input of approximately 1.6 MBTU/h was held constant throughout the testing. The combustion gases, at the end of the radiant section, are split into two convective passes, one on each side of the radiant combustion chamber. The gases exiting the convective section are cooled to below 500°F in an economizer located on top of the combustion chamber and then pass into a baghouse. The products of combustion (O_2, CO_2, CO, NO_x and SO_2) are monitored at the economizer outlet with a series of on-line gas analyzers. The ash samples were collected and analyzed for moisture and unburnt carbon to calculate the carbon burnout using the ash tracer technique as follows:

$$\text{Combustion Efficiency (\%)} = \left[1 - \frac{A_c(100 - A_r)}{A_r(100 - A_c)}\right] \text{x } 100$$

where, A_c = wt. percent ash in the coal, and A_r = wt. percent ash in the residue

Figure 3 shows a correlation between the Initial temperatures (from the burning profiles in a TGA) and the combustion efficiencies determined in the boiler. The plot shows a good correlation between the burning profile data and the combustion efficiencies as determined in the boiler. However, the flue gas oxygen levels were 5.5 and 5.9% for the Indonesian and PA coals, whereas for the Upper Freeport coal the boiler oxygen level was 6.5% and therefore, the combustion efficiency was slightly higher than expected from the interpolation. This underscores the importance of the operating conditions and sample characteristics.

Two bituminous coals were fired in a 15,000 lb/h industrial scale, demonstration boiler as micronized coals (80% passing through US standard 325 mesh instead of 80% passing 200 mesh). The boiler is a D-type package boiler designed for fuel oil. The boiler and auxiliaries are adapted with minor modifications to burn coal and coal-water slurry fuels. Details of the boiler can be found elsewhere (Pisupati et al., 1993). The combustion efficiency data obtained in the demonstration boiler is shown on Figure 3 as open diamonds. The combustion efficiency obtained for both coals was varying from 90 to 95% depending on the operating conditions such as excess air and fuel firing rate etc. The data plotted were for the conditions when the boiler oxygen was 3.2% and the firing rate was 14.8 MMBtu/h for both coals. The initial, peak, and the burnout temperatures for the Brookville bituminous coal were 310.8, 492.4 and 555°C, respectively. The initial, peak, and the burnout temperatures for the Kentucky bituminous coal were 313.8, 508.8 and 577.5°C, respectively. Very close initial temperatures reflected in close combustion efficiencies in the boiler under identical conditions. This also shows that the initial temepratures correlate well with the combustion efficiency. This probably is due to the earlier decomposition and thereby causing physical and chemical structural changes of the residual char earlier and hence a change in the reactivity.

Combustion Studies of blends of coals

One of the puzzling questions has been whether the characteristic temperatures obtained from burning profile hold good for blends of coals. Cumming (1989) has reported that the burning profile of a blend of coals of different rank (bituminous and anthracite) indicates that the fuels burn without interaction. Similar observations were made at this laboratory with bituminous and anthracite blends. However, blends of bituminous and lower lank coals indicated a linear correlation. Artos and Scaroni (1993) have shown that when a bituminous coal is blended with a subbituminous coal, the initial temperatures (IT) were proportionately lower with increasing percent of a subbituminous coal. The study also showed a linear increase in the combustion efficiency in the DTR with the addition of the subbituminous coal.

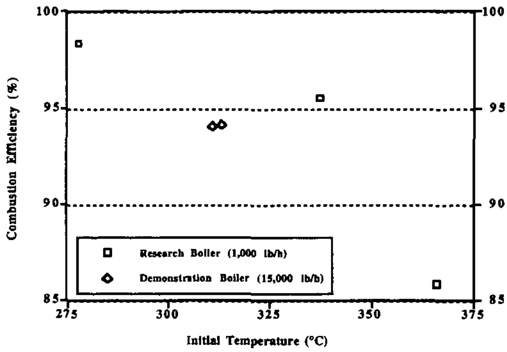

Figure 3. Correlation between the Initial Temperatures and the Combustion Efficiencies obtained in the 1,000 lb/h Research Boiler and in the 15,000 lb/h Demonstration Boiler.

In this study, an Indonesian subbituminous coal was blended with a Pennsylvania bituminous coal and the burning profiles and combustion behavior was determined in the TGA and the Research Boiler, respectively. The burning profiles are shown in Figure 4 for the Indonesian coal and blends with PA coal in various proportions. It can be clearly seen that there is a clear progressive increase in the characteristic temperatures with the increase in the proportion of the PA coal. This study confirms the observations of Artos and Scaroni (1993). The difference between the IT and the BT for the blends is higher indicating the initial decomposition starts at a lower temperature corresponding that of the lower rank coal in the blend and the combustion is not complete until the component with lower reactivity is burned. This suggests that there possibly is no influence of one coal on the other in a TGA. However, since there is a good correlation between the initial temperature and the combustion efficiency it may be concluded that blending coal which decomposes at lower temperature with less reactive coal, the former influences the combustion behavior of the latter in a boiler with self sustaining flame.

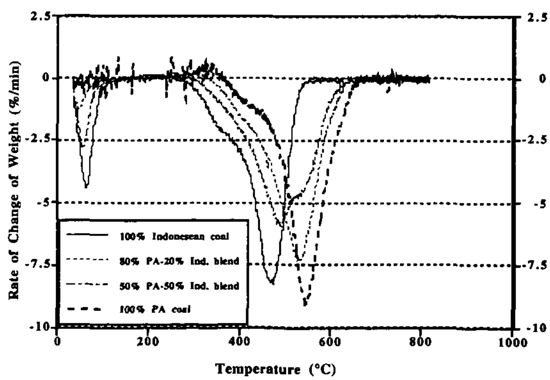

Figure 4. Burning Profiles of Pennsylvania Bituminous Coal Blends

Figure 5 shows a correlation between the initial temperature and the combustion efficiency obtained in the 1,000 lb/h research boiler for the coals and coal blends.

Summary

Burning profiles of a suite of coals ranging from fresh coals to severely weathered coals, and subbituminous coals and bituminous coals were obtained. Combustion efficiencies were also determined in a Drop tube reactor, 1,000 lb/h research boiler, and a 15,000 lb/h industrial scale demonstration boiler. A good correlation was obtained between the initial temperature and the combustion efficiency obtained under identical conditions was observed. A burning profile appears to be a good tool for evaluation of the relative combustion characteristics of fuels at a laboratory scale, when it is difficult, or there is not enough fuel, to test fire in a large installation.

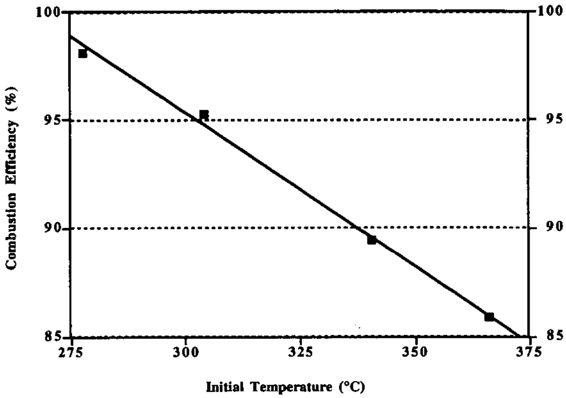

Figure 5. Correlation Between the Initial Temperatures and the Combustion Efficiencies Obtained in the Research Boiler

Because various investigators employed experimental conditions that were different from those originally proposed by Wagoner and Winegartner (1973), yet still obtained reproducible and interpretable results, it can be concluded that any laboratory using the technique of determining burning profiles to characterize the combustion behavior of coals can use their own reference standard conditions as long as all the samples (both the reference and unknown fuel) are tested under those standard conditions to obtain interpretable and meaningful data. However, it is not yet clear whether these profiles could predict the combustion efficiency of coal-water slurry fuels. The data generated under identical conditions may predict the combustion behavior of an unknown fuel under similar conditions. Those conditions may not be the optimum conditions for the fuel.

Acknowledgments

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