IGNITION BEHAVIOR OF PULVERIZED COALS: EXPERIMENTS AND MODELING

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INTRODUCTION

This paper reports the ignition temperatures, measured directly using two-color pyrometry, for three coals under various combinations of oxygen concentration and particle size. The measurements show that a range of ignition temperatures is measured under nominally identical experimental conditions, showing that particle-to-particle variations in size and reactivity must be accounted for. Our Distributed Activation Energy Model of Ignition (DAEMI), modified to account for these variations, is applied to the results to extract ignition rate constants.

We present data from a laser-based experiment used to measure the ignitability of pulverized coals in a room-temperature gas environment. The absence of hot furnace walls surrounding the test section allowed for optical detection of the ignition process. The experimental parameters studied include the coal type, oxygen concentration, particle size, and the temperature to which particles are heated by the laser pulse. The results show clearly that ignition reactivity is strongly dependent on coal type, and that the ignition rate constants determined are consistent with published data for overall combustion reactivity. The data also show convincingly that particle-to-particle variation in physical and/or chemical property of the fuel must be accounted for in order to model the ignition data correctly, and to accurately describe their ignition reactivity.

EXPERIMENT

The experiment is similar to one described in detail elsewhere,[1] so only a brief description is given here. Figure 1 presents a schematic of the laser ignition experiment; the inset shows the details around the test section. Sieve-sized particles were dropped through a tube into a laminar, upward-flow wind tunnel with a quartz test section (5-cm square cross-section). The gas was not preheated. The gas flow rate was set so that the particles emerged from the feeder tube, fell approximately 5 cm, then turned and traveled upward out of the tunnel. This ensured that the particles were moving slowly downward at the ignition point, chosen to be 2 cm below the feeder-tube exit. A single pulse from a Nd:YAG laser was focused through the test section, then defocused after exiting the test section, and two addition prisms folded the beam back through the ignition point. Heating the particles from two sides in this manner achieved more spatial uniformity and allowed for higher energy input than a single laser pass. For nearly every case, one to three particles were contained in the volume formed by the two intersecting beams, as determined by previous observation with high-speed video.[2]

The laser operated at 10 Hz and emitted a nearly collimated beam (6-mm diameter) in the near-infrared (1.06 μm wavelength). The laser pulse duration was ~100 μs and the pulse energy was fixed at 830 mJ per pulse, with pulse-to-pulse energy fluctuations of less than 3%. The laser pulse energy delivered to the test section was varied by a polarizer placed outside of the laser head; variation from 150 to 750 mJ was achieved by rotating the polarizer. Increases in the laser pulse energy result in heating of the coal particles to higher temperatures. At the ignition point the beam diameter normal to its propagation direction was ~3 mm on each pass of the beam. An air-piston-driven laser gate (see Fig. 1) permitted the passage of a single pulse to the test section. The system allowed for control of the delay time between the firing of feeder and the passage of the laser pulse. Finally, ignition or non-ignition was determined by examining the signal generated by a high-speed silicon photodiode connected to a digital oscilloscope. Figure 2 shows typical signal traces from the photodetector for both ignition and non-ignition events. Features of the trace for the ignition case is similar to that described previously.[1]

Particle temperature was measured by two-wavelength pyrometry. A simple lens coupled to an optical fiber bundle collected light emitted by the igniting particles. The output from the fiber bundle is collimated and separated into two beams via a dichroic filter. Light of wavelengths below 0.75 μm (the dichroic filter's cut-off wavelength) was passed through a bandpass interference filtered centered at 0.7 μm with a optical bandwidth of 40 nm. The remaining light was passed through an interference filter centered at 0.9 μm with an optical bandwidth of 10 nm. Separate high-speed silicon photodiodes detected each beam following the optical filters. The pyrometer was calibrated using a 2-mm diameter blackbody source at 990°C. Figure 3 shows typical signals from the photodetectors for a representative run, and the resulting temperatures measured.

We have examined the ignition behavior of three coals: one subbituminous, and two high-volatile bituminous. All samples were obtained from the Penn State University Coal Sample Bank, and the reported proximate and ultimate analyses are shown in Table 1. The coals were sieve-sized using a Ro-Tap shaker, and dried at 70°C under vacuum for at least 12 hours prior to each day's experiment.

RESULTS

Each day's experiment was conducted as follows: After choosing the coal and oxygen concentration to examine, the coal was loaded into the batch-wise feeder. The delay time between the triggering of the feeder and the appearance of the coal batch at the feeder tube exit was measured by visual observation in conjunction with a stop watch; typical values were 2.3-2.9 s. The delay time was then programmed into the electronic trigger device that triggered the laser gate. The gas flow rate needed to achieve a drop distance of ~5 cm for the coal batch was also determined by visual observation. Finally, a laser pulse energy was chosen, and the experiment commenced. At each set of operating conditions (coal type and size, oxygen concentration, and laser energy), 20 attempts at ignition were made in order to measure the ignition frequency, or probability, which is the parameter sought from these studies. Mapping this ignition frequency over a range of laser pulse energy produces an ignition-frequency distribution.

Such a frequency distribution is shown in Fig. 4 for the Pittsburgh #8 coal. It can be seen that at each oxygen concentration, ignition frequency increases monotonically over a range of laser pulse energy. Below this range the ignition frequency is zero, and higher energies result in 100% ignition frequency. This behavior is due to the fact that, within any coal sample, there exists a distribution of reactivity among the particles.[3] Thus, in this experiment, in which a batch of perhaps several hundred particles of a sample is dropped into the test section but only a few are heated by the laser pulse, there is an increasing probability (or frequency) as the laser energy is increased that at least one of the heated particles is reactive enough to ignite under the given conditions.

Figure 4 also shows the effect of oxygen concentration: As oxygen level is decreased from 100% to 50%, the frequency distribution shifts to higher laser energies or, equivalently, higher particles temperatures, as expected. This is consistent with ignition theory since at decreased oxygen levels, higher temperatures are necessary for heat generation by the particles (due to chemical reactions) to exceed heat loss from the particles and lead to ignition. The shift in distribution can be viewed in two ways: First, for a fixed laser pulse energy, a decrease in oxygen level leads to a decrease in the ignition frequency, all else being the same; second, a decrease in oxygen implies that a higher laser pulse energy is needed, in order to achieve the same ignition frequency.

The variation in temperatures measured for separate runs under identical conditions show the existence of particle-to-particle variations in the sample. Ignition temperature variations of up to 300 K is observed from run to run. This variation is due to the combination of reactivity and/or particle size differences between runs.

DISCUSSION

Over the past three decades, many experiments have examined the ignition of pulverized coals under conditions which simulate pulverized fuel-firing conditions.[4,5,6,7,8,9] The common factor among these studies is the assumption of a single, average, kinetic rate-constant in describing the ignition reactivity of each coal. As we have shown previously,[3] it is necessary to account for the variation in reactivity among the particles within a sample in order to model the ignition distribution observed in this and nearly all previous ignition studies. Once such a model is implemented, the parameters may then be adjusted to fit the data and produce the desired ignition rate constant and reaction order with respect to oxygen for each coal.

Our previous experience in modeling ignition distribution data[3] provides some insight to explain the results described earlier. The model details will not be described here, but it is sufficient to note that the model accounts for particle-to-particle variations in reactivity by having a single preexponential factor and a Gaussian distribution of activation energies among the particles within a sample. The distribution is characterized by two parameters, an average activation energy (E_o) and a standard deviation (σ) in the activation energy.

In light of this model, the differences in the range of laser energies over which the various coals achieved 100% ignition frequency is a direct result of the breadth of the distribution of activation energies: A narrow distribution (small standard deviation) leads to a small laser-energy range since most particles have similar activation energies and, thus, reactivities. Indeed, in the limit that the standard deviation is zero (all particles have the same activation energy), the ignition-frequency distribution would become a step function from 0 to 100% ignition frequency. Conversely, a broad distribution of reactivities (large σ) leads to a relatively larger range of laser energy needed to achieve 100% frequency. The effect of variations in the average value of the activation energy (E_o) in the distribution is to shift the ignition-frequency plot; higher E_o means lower ignition reactivity for a particular coal, which shifts the ignition distribution to higher laser energies.

Finally, with regard to the effect of oxygen concentration on the slope and shift of the ignition-frequency distributions observed for the Pittsburgh #8 coal, the model interprets such differences to be the result of the variation in the reaction order, n, with respect to oxygen concentration.

ACKNOWLEDGEMENT

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REFERENCES

1 Chen, J.C., Taniguchi, M., Narato, K., and Ito, K. "Laser Ignition of Pulverized Coal," *Combust. Flame* 97, 107 (1994).

2 Chen, J.C., Taniguchi, M., Ito, K. "Observation of Laser Ignition and Combustion of Pulverized Coals," *Fuel*, 74(3), 323 (1995).

3 Chen, J. C. "Distributed Activation Energy Model of Heterogeneous Coal Ignition," *Combust. Flame*, 107, 291 (1996).

4 Essenhigh, R.H., Mahendra, K.M., and Shaw, D.W. *Combust. Flame*, 77, 3 (1989).

5 Cassel, H.M. and Liebman, I. *Combust. Flame*, 3, 467 (1959).

6 Karcz, H., Kordylewski, W., and Rybak, W. *Fuel*, 59, 799 (1980).

7 Fu, W. and Zeng, T. *Combust. Flame*, 88, 413 (1992).

8 Zhang, D., Wall, T.F., Harrie, D.J., Smith, I.W., Chen, J., and Stanmore, B.R. *Fuel*, 71, 1239 (1992).

9 Boukara, R., Gadiou, R., Gilot, P., Delfosse, L., and Prado, G. *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, PA, 1993, pp. 1127-1133.

Coal		Prox. Analy. (dry wt%)		Ultimate Analysis (dry, ash-free wt%)				
Penn State ID	Rank	Vol. Matter	Ash	C	H	N	S	O (diff.)
Wyodak (DECS 26)	Subbituminous	44.9	7.59	69.8	5.65	0.94	16.1 (O+S)	-
Pittsburgh #8 (DECS 23)	high-volatile A bituminous	39.4	9.44	82.0	5.63	1.49	4.27	6.66
Illinois #6 (DECS 24)	high-volatile C bituminous	40.8	13.4	66.1	4.59	1.14	14.8 (O+S)	-

Table 1: Ultimate and proximate analyses of coals used in this study.

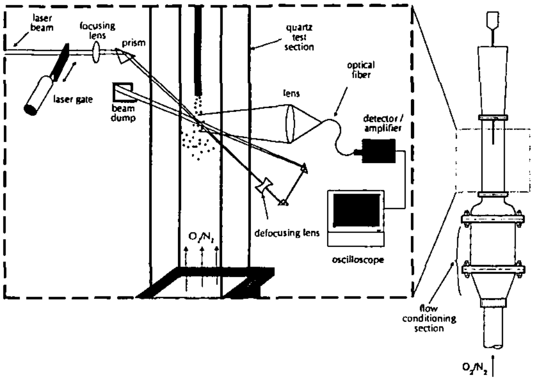

Fig. 1: Schematic of the laser ignition experiment.

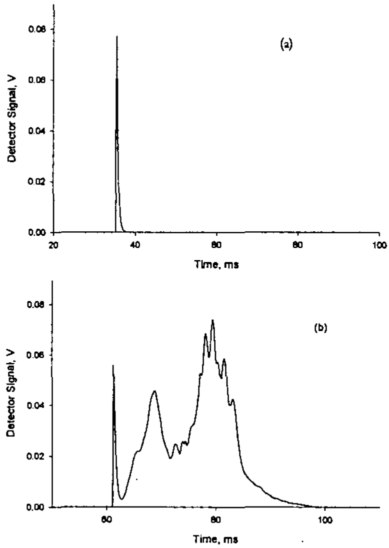

Fig. 2: Signal traces from photodetectors showing (a) non-ignition and (b) ignition events for the Pittsburgh #8 bituminous coal. Particle size was 125-158 μm, and oxygen concentration was 100%.The short-lived spike in both traces result from laser heating of the coal surface and subsequent cooling. Ignition and combustion of the coals causes the long-lived emission of (b).

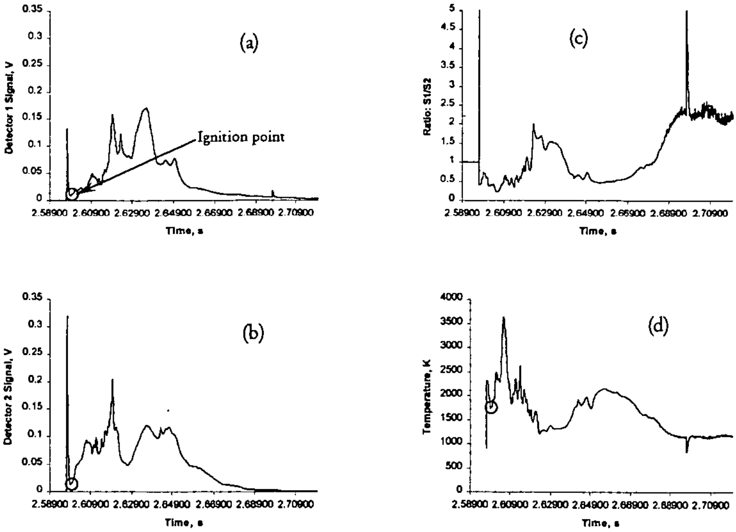

Fig. 3: Representative signal traces from experimental run with Pittsburgh #8 high-volatile bituminous coal showing (a) the signal at a wavelength of 0.9 μm, (b) the signal at a wavelength of 0.7 μm, (c) the ratio of signals, and (d) the interpreted temperatures. The ignition point is marked by circles in (a), (b) and (d).

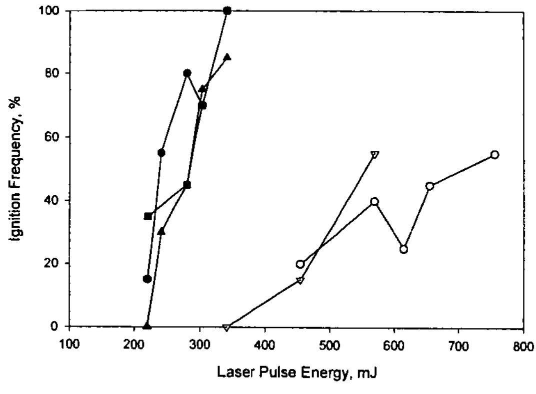

Fig. 4: Ignition-frequency distribution of Pittsburgh #8 (DECS-23) coal, 125-150 μm diameter. Solid symbols are data taken at 100% oxygen concentration, and open symbols are data for 50% oxygen concentration.