IGNITABILITY OF VARIOUS COALS AS MEASURED BY LASER IGNITION

John C. Chen,[†] Subrahmanyam Musti,[*] Vinayak Kabadi[*]
Departments of [†]Mechanical and [*]Chemical Engineering
North Carolina A&T State University
Greensboro, NC 27411

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INTRODUCTION

We present a novel experiment designed to study the ignition and combustion of pulverized fuels in a room-temperature gas environment. The absence of hot furnace walls surrounding the test section allowed for optical detection of the reaction sequence. Our goals are to determine, by direct observation, the ignition mechanism (heterogeneous or homogeneous ignition) of a range of coals, and to quantify the differences in ignition reactivity between the fuels.

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, two to five 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 after the laser exit; 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 nonignition was determined by examining the signal generated by a high-speed silicon photodiode connected to a digital oscilloscope, as described elsewhere.[1]

We report here the ignition behavior of four coals ranging in rank from subbituminous to medium-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 to -120/+140 mesh (106-125 μm diameter), 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 ~ 2.9 s. The delay time was then programmed into the device which 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. 2 for the Pittsburgh #8 coal. It can be seen that at each oxygen concentration, ignition frequency increases monotonically over a range of increasing 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 variation 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.

The repeated distributions under 100% oxygen, measured on separate days, show the excellent repeatability of this experiment; the most important factor for reproducibility is the moisture content of the sample.

Figure 2 also shows the effect of oxygen concentration: As oxygen level is decreased from 100% to 75%, and then 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 to achieve the equality between heat generation by the particles (due to chemical reactions) and heat loss from the particles. This equality is the minimum requirement for ignition, and is termed 'critical 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.

Finally, it should be noted that for the Pittsburgh #8, the decreases in oxygen concentration shift the distributions to higher laser energies in approximately equal increments (equal energy ranges), and with little or no effect on the slope of the distributions. This finding is in contrast to the results for the Sewell coal (Fig. 3).

Three major differences between the ignition behaviors of the Pittsburgh #8 and Sewell exist. First, decreasing oxygen concentrations has a stronger effect in shifting the distributions of the Sewell to higher laser pulse energies (or higher particle temperatures). Second, as oxygen level is decreased, the slope of the distribution is undoubtedly decreased for the Sewell, while little effect is observed for the Pittsburgh #8. Finally, a comparison of the distributions of the two coals under 100% oxygen shows that the Sewell reaches 100% ignition frequency in a significantly smaller range of laser energy (~150 mJ versus ~250 mJ).

The results for the two remaining coals — the Illinois #6 and the Wyodak — are shown in Figs. 4 and 5. The two coals span similar ranges in going from 0 to 100% ignition frequency (~350 mJ), which are larger than both the Pittsburgh #8 or Sewell coals. Comparing the results for these two coals, it is also observed that the ignition-frequency distributions of the Illinois #6 are shifted to higher laser energies than the Wyodak, implying that the Illinois #6 is a less reactive coal, at least with regard to ignition.

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.

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 Gaussian 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. Conversely, a broad distribution of reactivities leads to a relatively larger range of laser energy needed to achieve 100% frequency, as is the case for the Pittsburgh #8 compared to the Sewell. The fact that the Illinois #6 and Wyodak coals span a similar laser-energy range suggests that the spread of their reactivity distributions are similar. However, since the ignition-frequency distributions of the Illinois #6 are shifted to higher laser energies than the Wyodak, the interpretation is that the reactivity distribution of the Illinois #6 has a lower average activation energy, and therefore it is more reactive, as stated earlier.

Finally, with regard to the effect of oxygen concentration on the slope and shift of the ignition-frequency distributions observed for the Pittsburgh #8 and Sewell coals, the model interprets such differences to be the result of the variation in the reaction order with respect to oxygen concentration. We are presently at work on modeling the results reported here, with the goal of presenting kinetic rate parameters in the near future.

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Coal		Prox. Analy. (dry wt%)		Ultimate Analysis (dry, ash-free wt%)				
Penn State ID	Rank	Vol. Matter	Ash	C	H	N	S	O (diff.)
Pittsburgh #8 (DECS 23)	low-volatile A bituminous	39.4	9.44	82.0	5.63	1.49	4.27	6.66
Sewell (DECS 13)	medium-volatile bituminous	25.0	4.22	88.2	4.95	1.50	0.65	4.71
Illinois #6 (DECS 24)	high-volatile C bituminous	40.8	13.4	76.3	5.30	1.32	6.38	10.74
Wyodak (DECS 26)	subbituminous B	44.9	7.57	75.5	6.11	1.02	0.47	16.92

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

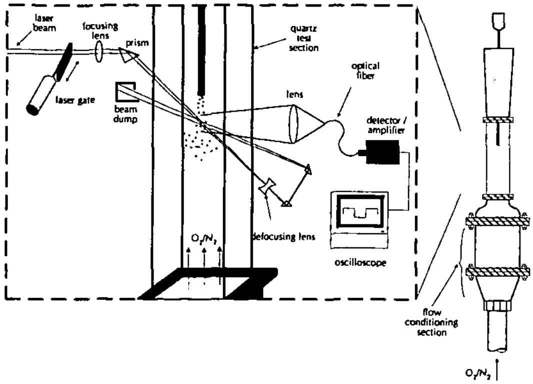

Fig. 1: Schematic of the laser ignition experiment.

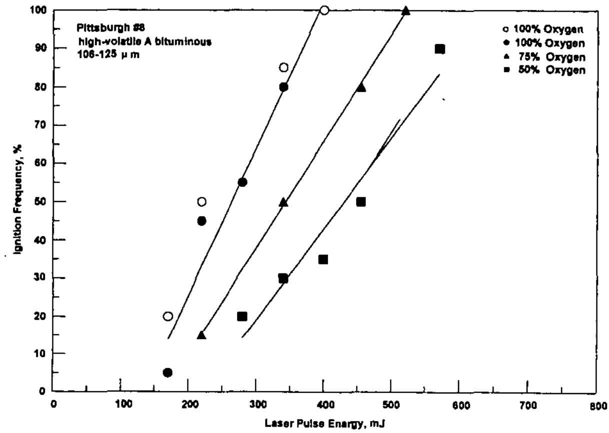

Fig. 2: Ignition-frequency distributions for the Pittsburgh #8 coal. Two data sets (open and filled circles) at 100% oxygen show reproducibility of experiment.

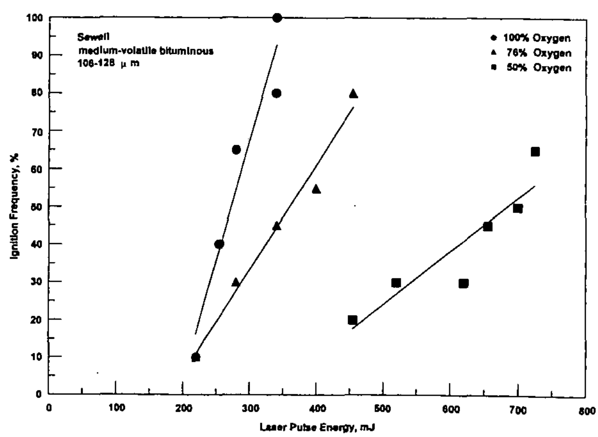

Fig. 3: Ignition-frequency distributions for the Sewell coal.

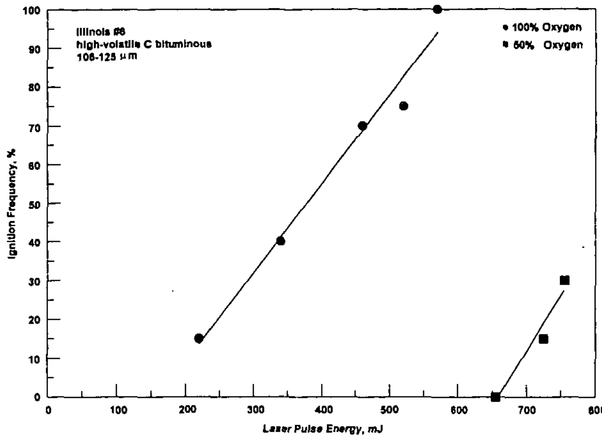

Fig. 4: Ignition-frequency distributions for the Illinois #6 coal.

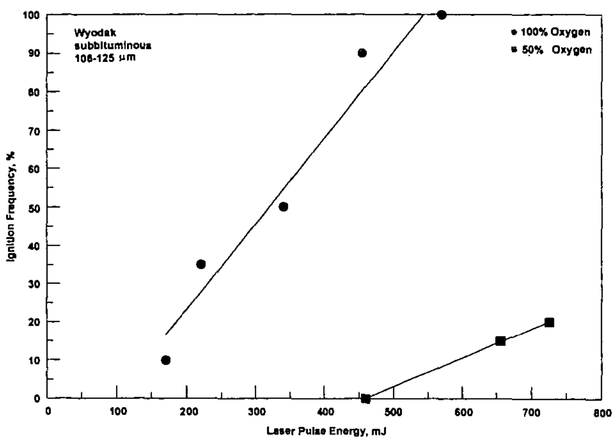

Fig. 5: Ignition-frequency distributions for the Wyodak coal.