DIRECT OBSERVATIONS OF DEVOLATILIZING PULVERIZED COAL PARTICLES IN A COMBUSTION ENVIRONMENT

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Direct observations of the early stages of combustion of size-graded (~100μm) pulverized coal particles are reported. The particles are introduced on the centerline of a high temperature, transparent, laminar flow reactor fed by a gas fueled, premixed flat flame. Photographs of particle emission, high magnification shadowgraphs of burning particles, and micrographs of partially burnt captured material have been obtained. The ignition of both bituminous coal and lignite subjected to rapid heating (~10⁵ K/sec) by hot combustion products is characterized by bright diffuse emission attributed to burning of ejected volatile matter. After approximately 5 msec this emission ceases, and incandescence attributed to heterogeneous char oxidation is observed.

Shadowgraphs and micrographs of burning bituminous coal indicate that, coincident with ignition, ejected volatile matter forms a condensed phase surrounding the particle. The condensed phase is evidently a soot-like material resulting from pyrolytic cracking of hydrocarbons in the volatile matter. Viscous drag forces cause the condensed material to be swept into laminar wake structures which eventually separate from the particles. Under oxidizing conditions this condensed volatile matter is oxidized during the early stages of char burning, while under reducing conditions it persists throughout the flow reactor.

Although burning lignite appears similar to bituminous coal in emission, shadowgraphic and micrographic observations indicate that a condensed phase is not formed during devolatilization. Nor are changes in particle size or shape observed during the earliest stages of combustion. These observations are consistent with previous results which showed that bituminous coal volatiles contain large fractions of soot producing heavy hydrocarbons, while lignite volatiles are largely composed of CO, CO₂, H₂, H₂O and light hydrocarbons. The observations are also consistent with differences in the pore structure and swelling properties of the two coals.

Introduction

In order to better define the details of the physical and chemical processes which occur during combustion or gasification of pulverized coals, we are conducting laboratory experiments which permit direct observation and measurement of events and parameters associated with the early stages of reaction of individual coal particles entrained in combustion environments. In recent years much attention has been directed at obtaining a better understanding of the processes which occur during the first few milliseconds of combustion and gasification of pulverized coals at high temperatures and high heating rates. This represents a significant shift from earlier studies which sought to describe the overall combustion process and consequently emphasized the rate limiting process of char burn-up.

Experimental studies of ignition and devolatilization of pulverized coals at high heating rates (~10 to 100 K/msec) have greatly improved our general understanding of these processes. However, important details of rates and mechanisms of ignition and devolatilization as a function of the properties of the coal and the surrounding environment remain unresolved. Mechanisms of coal ignition remain debatable.

In the present work we report our observations of some of the processes which take place during ignition and devolatilization of pulverized coal particles. Observations are made for freely entrained pulverized coal particles in high temperature oxidizing environments under rapid particle heating rates.
The experiment is designed to simulate the local particle loading densities and thermal and chemical environments encountered when pulverized coals are injected into practical combustors. The initial data reported here document several striking and potentially significant phenomena which distinguish the ignition and devolatilization of bituminous coal and lignite.

Experimental Apparatus and Procedure

This study involves the observation of the first 100 msec of combustion of two pulverized coals, a Pittsburgh seam bituminous coal and a North Dakota lignite. The experiments are conducted at atmospheric pressure in a high temperature oxidizing environment provided by a laminar flow reactor. The reacting environment is provided by the uniform and well-controlled post-flame gases of a premixed, laminar flat flame. In the present investigations mixtures of methane, hydrogen and air were used to produce uniform reactor carrier gases at temperatures from 1100 K to 1800 K with oxygen mole fractions of 0 to 0.20. Under these conditions, axial and radial temperature profiles in the reactor, in the absence of coal were measured. Within the first 200 mm (~200 msec) of the burner surface the radial temperature profile is essentially flat within ±1 cm of the centerline. Due to heat loss, the axial temperature gradient is approximately -1 K/mm.

Coal particles are injected into the reactor in a dilute single stream on the centerline of the reactor, through a 1 mm diameter capillary tube which partially protrudes through the burner grid. Pulverized size-graded coal particles are supplied to the capillary tube by a pressurized two-stage spouted fluidized bed feeder of the type described by Hamor and Smith. An important feature of this apparatus is that the stoichiometry and velocity of the coal feeder carrier gas and the supporting flame gases are matched. Thus the coal is introduced into a uniform reaction environment. The particle loadings delivered by the feeder can be varied to match the particle loadings in different regions of practical pulverized coal flames. For this configuration, the velocity of the hot, laminar reactor gas is sufficiently low and uniform (approximately 10 mm/msec) and the coal particle size sufficiently small (<100 μm mean diameter) that the particles are in Stokes flow in the reactor. The overall experimental technique is similar to one employed by Friedman and Macek to study combustion of aluminum particles.

The coals were prepared for these experiments by grinding, impact milling and air-centrifuge classification. The present experiments were conducted with a bituminous coal sample pulverized to a mass mean size of 65 μm with a standard deviation of about 10 μm; for the lignite sample the mass mean particle size was 100 μm but with a somewhat larger standard deviation. The bituminous coal has been the subject of several previous, related studies, while the lignite is representative of sodium containing Western lignites, which are increasingly being used and which exhibit troublesome ash fouling behaviors.

In the present study, processes which occur during the very earliest phase of pulverized coal combustion have been directly observed and recorded by still photography and by high speed cinephotography. Extensive information has been obtained from shadowgraph images of the reacting coal particles at high magnification. The flow reactor is back lit with collimated light from a high intensity source. Shadow images are obtained using a two lens collection system with a 20x microscope objective serving as the camera lens. For single shadowgraphs, a strobe light source with a 1 μsec flash is synchronized with a 35 mm camera shutter; the collection optics provide a magnification of approximately 20 at the plane of the black and white film. Resolution of a few microns is easily achieved. High speed cine-shadowgraphs have been obtained using a Hycam camera and a continuous high pressure mercury light source. Various magnifications and fields of view (e.g. 1 to 10 mm along the reaction coordinate) have been used. Larger fields of view with lower magnification permit observation of a larger portion of the devolatilization process for several particles simultaneously, i.e., in the space of a single frame. This also allows observation of individual particles for times up to 5 msec. In a few cases the direct photographic information is substantiated by microscopic examination of deposits of partially reacted coal and condensed solids at various stages of the devolatilization process.

In several previous studies inquiries have been raised as to the dependence of the data on the experimental configuration (see also the discussions following Refs. 7 and 17). Questions remain as to the relative influence of e.g., heating and quenching rates for suspended coal samples and the nature of the sample environment—vacuum, inert gas, or, reactive gases—on particle ignition and on the rate of evolution and chemical composition of volatile matter. Only a few fundamental studies, for example, have been conducted in oxidizing environments.

The present flow reactor technique has a number of advantages over alternative methods for obtaining information on the time scale of the rapid devolatilization processes which occur during pulverized coal combustion. These are:

- The temperature and composition of specific regimes in practical coal-fired combustors may be simulated, viz., gas temperatures of 1000 to
2000 K, oxygen mole fractions of 0 to 0.20, particles less than 100 μm in diameter, particle heating rates approximately 50 to 200 K/msec, and residence times 1 to 200 msec.

- The residence time of the particles in the thin supporting flame zone at the burner surface is sufficiently short (<1 msec) that the only influence of the gas flame should be to initiate particle heating.
- With the coal particles in Stokes flow, the velocity of the reactor gases is nearly optimal for stretching the reaction time coordinate sufficiently for detailed observation with adequate time (<1 msec) and space (<1 mm) resolution of devolatilization and combustion.
- The experimental configuration facilitates optical and sampling probe access.

Results

1. Bituminous Coal

The bituminous coal and lignite have been tested in the flow reactor, and various physical phenomena associated with devolatilization and ignition have been identified. Figure 1 is a photograph showing the visible emission from the bituminous coal as it enters the post flame environment, is heated, and ignites. Eight percent oxygen is available in the post-flame gases on a complete combustion basis. Individual particles traveling at approximately 2 mm/msec pass entirely through the field of view while the camera shutter is opened, leaving a streak record on the film. Particles are observed to continue into the post flame gases for about 2-3 msec whereupon bright yellow emission abruptly begins. We refer to the location of the onset of this bright emission as the ignition point. Following this ignition point, the particles exhibit a distinct bright zone lasting about 5 msec, and this zone is followed by less bright, incandescent particle tracks through the remainder of the reactor. The initial bright zone is thicker and more diffuse than the following incandescent zone, and in some cases a bright particle streak can be seen within this diffuse region. Similar "ignition" characteristics are observed over a wide range of lean fuel-air mixtures and temperatures in the premixed gas flame.

High magnification, short duration shadowgraphs (both still and cine) give clear evidence of physical phenomena associated with the earliest phases of pulverized coal combustion. Figure 2 shows still camera shadowgraphs (taken under the same flame conditions as Fig. 1) at the ignition point (Fig. 2a), about halfway through the bright region (Fig. 2b), and at the end of the bright region (Fig. 2c). The particles in Fig. 2a are surrounded by a dark region due to the presence of a condensed phase, which forms locally in the surrounding region or which may be ejected from the particle. The ignition point in all cases is coincident with the first appearance in the shadowgraphs of such a condensed phase surrounding the particles (Fig. 2a). The condensed material extends outwards more than one particle diameter, and within a few milliseconds is swept around the particle into a tail or wake structure (Fig. 2b). Individual particles can be discerned within the wakes of condensed material, with sizes down to a few microns. The development of the wakes (generally, but not always, ahead of the particle in laboratory coordinates) is due to a small slip velocity between the particle and the gas. Reynolds numbers based on this slip velocity and the diameter of the condensed zone are of order unity, and the long thin wakes observed are characteristic of laminar wakes around spheres at very low Reynolds numbers. Some of the smaller scale features in Fig. 2b appear to result from individual sites on the coal particles and suggest ejection from pores. Within
a few milliseconds after first appearance, the condensed material stops forming, and by the end of the visibly brighter region the particle wakes are extended ahead the particles (in a laboratory reference frame) and eventually separate from the particle (Fig. 2c). The wake formation dynamics can be seen in the sequential movie frames shown in Fig. 3. The frames are taken every 200 µs with 10 µs exposure duration. Although the wakes are in general smooth and aligned with the overall flow direction, some wakes are observed in opposite directions and many are curved or otherwise distorted. Relative motion between the particles and the wakes is usually due to velocity slip (particle drag) in the flow direction, although transverse separation of the particle and the wake is occasionally observed, apparently caused by reaction to jetting of volatile matter from individual pores. An example of such separation can be seen in Fig. 3.

As noted above, the onset of intense luminosity associated with particle ignition at high temperatures is, in all cases, coincident with the first appearance in the shadowgraphs of the condensed phase material around the particle. High speed shadowgraphs of this ignition zone, obtained by aligning the camera axis with a laser, confirm that these events are coincident to within 1 msec. Furthermore, for temperatures below 1100 K, we observe neither the distinct bright emission nor the appearance of condensed volatile matter which are characteristic of ignition at higher temperatures. At these lower temperatures only dull, faint thermal emission from hot particles can be observed. Although not conclusive, the evidence in the present high heating rate experiments seems to indicate that combustion is initiated by ignition of volatile matter expelled during particle heating.

Still and motion pictures have been taken at several locations through the flow reactor to examine the eventual fate of the condensed wake material de-
scribed above. Within 2–3 msec after the end of the brighter zone (i.e., 7–8 msec after ignition) essentially all of the "tails" have further elongated and separated from the particles. In cases where free oxygen is present (i.e., when the gas flame is lean) the condensed structures gradually disappear, apparently due to oxidation. For example, at 1700 K and 8% oxygen, "stringy" condensed structures, several millimeters in length, and sometimes curved or otherwise distorted, are still observed 15 msec after ignition, although they are considerably lower in number density than the particles. By 50 msec after ignition, essentially all the condensed material has been oxidized, and the shadowgraphs show only solid char particles again.

The fate of the condensed material depends strongly upon the gas flame stoichiometry. When the gas mixture is adjusted to give 20% oxygen and the same 1700 K temperature in the post-flame gases, the onset of bright emission is observed after the same time delay, but is enormously brighter and persists for a shorter time. The condensed material
is consumed in 25 msec at 20% $O_2$ compared to 50 msec at 8% $O_2$. If the gas flame is rich, the condensed material does not oxidize, but rather persists through the entire reactor. The initial formation of the particle wakes is similar to the lean flame cases, although the direct emission does not exhibit a sharp distinction between an initial brighter zone and a subsequent cooler, distinct incandescent particle track.

From consideration of information provided by the shadowgraphs and by direct emission, a qualitative picture of the bituminous coal devolatilization and ignition processes is constructed. Upon encountering high heating rates ($\sim 10^2$ K/msec) in an oxidizing combustion environment, the particles rapidly heat and eject volatile matter, some of which rapidly forms a condensed soot-like material in the region surrounding the particle. The condensed phase forms more or less uniformly around the particle on a sub-millisecond time scale, and is then drawn into wake structures by viscous forces. The condensed material is attributed to formation of a soot-like material due to pyrolytic cracking of the heavier hydrocarbons in the volatile matter followed by rapid dehydrogenation, polymerization and condensation of the pyrolysis products. In an oxidizing environment this carbonaceous material eventually oxidizes and disappears as gaseous product. Some of the ejected volatile matter burns immediately, near the particle, producing a very bright emission which persists for about 5 msec. This distinctively bright zone is evidently associated with the diffusion limited burning of some of the hydrocarbon components of the volatile matter. Previous photographic studies of the combustion of individual pulverized coal particles have also shown the bright, diffuse emission (similar to that of Fig. 1) in the earliest stages of combustion, and such emission has been attributed to the burning of volatile matter.

The present observation of the formation of a condensed soot-like material during coal devolatilization in a combustion environment is the first direct photographic observation of this phenomenon, although previous holographic studies provided a similar result for a high volatile bituminous Utah coal. Flow reactor studies of the devolatilization of sub-bituminous and bituminous coals have also indicated that a fine soot-like material is formed under rapid heating conditions. A previous study of the devolatilization of a Pittsburgh seam bituminous coal in a combustion environment also inferred the formation of soot via pyrolysis of hydrocarbon volatiles, and this study indicated that approximately 15% of the volatile matter may form a soot-like material.

Material collected on quartz slides held briefly in the burning coal stream provides further information on the condensed phase formed during devolatilization and substantiates our interpretation of the shadowgraphs. Photomicrographs of such material are shown in Fig. 4. The particles shown in Fig. 4a were collected prior to particle ignition, but after passage through the gas flame. The particles appear to have melted and swelled and some have a glassy window from which a void may develop. The material shown in Fig. 4b was collected on a slide held in the bright devolatilization region, and exhibits the stringy soot-like material seen in the shadowgraphs. On examination at higher magnifications this material appears to be composed of agglomerates of finer material, the smallest of which is about 100 Å in diameter and looks like flame-generated soot. The material in Fig. 4c was collected at the end of the brighter emission region. The stringy material is now separated from the particles and oxidation has begun. The slide shown in Fig. 4d contains material collected after 50 msec reaction time, well after the bright devolatilization zone. Here all the soot-like material has been oxidized and only the remaining char particles are seen on the slide.

2. Lignite

A comparison of the behavior of burning lignite under similar conditions has been carried out. Visible emission from burning lignite particles with the same reactor conditions gives an overall appearance similar to the bituminous coal. That is, after a few milliseconds heat-up time, ignition is characterized by bright, somewhat diffuse emission persisting for approximately 5 msec, followed by sharply defined traces due to incandescent solid particles. In addition, the lignite exhibits a very diffuse yellow-orange emission which we have identified by spectroscopy as sodium D-line emission. Sodium levels in lignites from the North Dakota region are known to be higher than in bituminous coal; this particular lignite contained 2.8% Na₂O by weight in the ash.  

While the direct visible emission from burning lignite is quite similar to that of the bituminous coal, the information obtained via high magnification

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**Fig. 4. Photomicrographs of captured burning bituminous coal particles:** (a) prior to ignition, (b) several msec after ignition, (c) approximately 10 msec after ignition, (d) 50 msec after ignition.
tion shadowgraphs indicates considerable differences in the devolatilization processes of the two coals. Shadowgraphs obtained prior to ignition, during the region of bright emission, and immediately above the bright emission region appear similar to each other. Thus, the ignition, devolatilization and initial burning of the pulverized lignite take place without significant changes in particle shape or size, and without formation of sufficient condensed material to be observed in the shadowgraphs. No significant off-axis motion of reacting lignite particles is observed, which suggests uniform release of volatiles over the exterior surface of these particles.

Two micrographs of slide-captured lignite particles are shown in Fig. 5. The particle in Fig. 5a was captured a few milliseconds after ignition, while the particles in Fig. 5b were collected 40 msec after ignition. Figure 5a shows no evidence of condensed material, consistent with the absence of such material in the shadowgraphs. The particles in Fig. 5b appear to have their surfaces eroded by the oxidation process, and the surface appendages are largely agglomerated molten ash.

Discussion

The observed major differences between the behavior of the bituminous coal and the lignite are thought to be related to differences in the basic chemical and physical structures of these materials. First, during rapid devolatilization, bituminous coals are known to produce an abundance of light and heavy hydrocarbons while lignites produce mostly CO, CO₂, H₂O, H₂ and light hydrocarbon gases. In both cases evolution and burning of light hydrocarbons near the particle is apparently responsible for the initial diffuse bright region associated with ignition. Evidently only the bituminous coal produces quantities of heavy hydrocarbons sufficient for soot formation.

In addition to the chemical structure of the devolatilized matter, we feel that physical properties of the bituminous coal, in particular pore structures and melting and swelling characteristics, contribute to the formation of condensed material during ignition and devolatilization. At high temperatures, a bituminous coal particle melts (in particular the vitrinitic components), loses porosity, evolves light and heavy gases within the particle, and eventually ejects some of this material into the surroundings. Polymerization of some of the volatile components most likely occurs both prior to and after ejection. A swollen bituminous coal particle acts as a thermal reactor which restricts volatile evolution, and in which heavy tar-like volatile matter can polymerize. In contrast, the pore structure of the lignite coals opens and allows free evolution of volatile matter during particle heat-up, ignition and devolatilization. From these limited experiments we suspect that only swelling coals, with carbon contents between 75 and 90 percent on a dry mineral matter free basis will produce condensed, soot-like material during devolatilization at high temperatures and high heating rates.

The presence of a condensed phase during devolatilization potentially affects several aspects of practical combustion of coal. These are: formation and emission of soot, the effect of soot on radiative heat transfer, the effect of soot on ignition and flame stability, and the effect of soot on the formation of nitrogen oxides from fuel nitrogen. All these effects will become more important as richer primary stages are employed to control NOₓ. While the highly turbulent flows characteristic of practical burners may disrupt the dramatic hydrodynamic wake structures seen in our laminar flow experiments, we nevertheless expect the initial soot formation process to remain much the same as observed here.

Conclusions

A transparent laminar flow reactor, fed by a flat hydrogen-methane-air flame, has been successfully used to examine the ignition and devolatilization of size-graded coals under various combustion conditions. The flow reactor is capable of simulating the conditions found in different regions of practical combustors.

Ignition of Pittsburgh seam bituminous coal is characterized by the onset of very bright emission around the particles, which we attribute to thermal radiation from soot formed from volatile matter. A fraction of the volatile matter forms a condensed soot-like phase which surrounds individual particles. Relative motion of the particles with respect to the gas causes this condensed material to form long thin laminar wakes behind the particles. The wakes become greatly elongated and eventually separate from the particles, forming strings of soot-like material many tens of particle diameters in length. Under oxidizing conditions, this material is

![Fig. 5. Photomicrographs of captured burning lignite particles; (a) several msec after ignition, (b) approximately 40 msec after ignition.](image)
rapidly oxidized, leaving only burning char particles. The oxidation of the condensed material takes 50 msec in the presence of 8% oxygen, but does not occur in rich flames. Ignition of the lignite is also coincident with the evolution and burning of volatile matter, however formation of condensed material near the particle is not observed.

We have shown that formation of condensed volatile matter is strongly dependent on coal type but only weakly dependent on local conditions over the range of temperatures and stoichiometries encountered in practical combustors. Previous inferences of significant jetting of volatiles and soot formation during devolatilization of bituminous coals at high heating rates are unambiguously confirmed by the present direct observations.

Acknowledgments

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REFERENCES

23. The lignite was obtained from the Pennsylvania State Coal Bank and is designated PSOC 246. The assistance of Professor Alan Davis, Coal Research Section, Department of Fuel Science, Pennsylvania State University, in obtaining the coal and a summary of its properties, including a recent analysis of the ash composition, is gratefully acknowledged.
25. Samuelson, G. S., Trolinger, J. D., Heap, M.
COMMENTS

N. Brown, University of California, USA. You have measured particle size at different flame locations. In one case, size was determined using electron microscopy following sample collection on slide; in the second case particle size was determined in situ via shadowgraph technique. How do the data associated with the two measurement techniques compare?

Author's Reply. The dimensions of the coal particles and the soot-like strings or tails were measured using in-situ shadowgraphs and optical micrographs of withdrawn samples. Good agreement was obtained between the two techniques both for the coal particles and for the soot-like material. For example, for the bituminous coal, particle sizes measured from the shadowgraphs (Figures 2 and 3 in the text) varied from an original particle size of 65 μm to a swollen particle size of 120 μm. Sizes measured from the micrographs (Figure 4a, text) varied from 65 μm to 105 μm. Thus the measurements agree, are consistent with other data, and show that bituminous coals can swell at least a factor of 1.85 in diameter. Particle sizes for the lignite determined by the same two techniques were also in agreement. Scanning electron micrographs of the soot-like material are discussed in the reply to Professor Ulrich's question.

G. Ulrich, University of New Hampshire, USA. Micrographs of what you term “condensed soot-like material” do not resemble those taken of soot from other sources. These filament-like structures differ from the more evenly-spaced morphology that characterizes soot aggregates. In addition, these linear particles are an order of magnitude larger than what I would expect from gas pyrolysis. Also, it is improbable that mobile soot particles, formed in the gas phase, would remain in the vicinity of the coal char.

Since both solid and gas are evident, it is logical to assume that hydrocarbon liquids are also present. Structures in your micrographs have the appearance of viscous liquid filaments which might have been expelled from the reacting coal particles. A few submicron soot aggregates may, however, have deposited on the surface. Do you think this alternative is a feasible one?

Author’s Reply. Professor Ulrich implies that the material we have identified as soot might as well be a liquid. No one can prove that the “soot-like” material is in fact soot, but all the indirect evidence indicates that it is and none indicates that it is a liquid. The size and morphology of the fine structure of the “soot-like” material closely resembles soot. A scanning electron micrograph of this material is shown in Figure 1. The long “soot-like” streamers are agglomerates of many chains which are in turn composed of individual particles 100-1000 Å in diameter. The individual particles have the proper chain structure and size to be soot. Small soot particles would indeed be swept away from the char particle by the small slip velocity present. This is exactly what is shown in Figures 2a, b, c and Figure 3 of the text. As such low Reynolds numbers the small particles are, however, swept into a relatively narrow wake region where agglomeration appears to occur.

The “soot-like” material appears to initially develop uniformly around, but a small distance from the char particle (Figure 2a and 3, text), and to develop a densely agglomerated phase as the volatile material is swept into the wake. This implies that initial volatile matter is gaseous. A liquid would

FIG. 1. Scanning electron micrograph of fine structure of “soot-like” material formed during bituminous coal devolatilization.
be expected to jet from individual pores, to cast a shadow at the char surface, and would itself form a soot at high temperatures.

We found no evidence in the withdrawn samples of a condensable liquid. A small amount of uniformly deposited tar was found in the early devolatilization region (Figure 4a, text). The uniform deposition of this material and the absence of it in the regions where "soot-like" material was formed indicate that the tar was present as a condensible gas and not a liquid.

Finally, Kobayashi and Pohl, in work done at MIT, determined the H/C ratio of the "soot-like" material from the same coal to be 0.04. This small amount of hydrogen indicates that this material is more likely to be soot than a condensed liquid hydrocarbon.

REFERENCES


L. D. Smoot, Brigham Young University, USA.

You indicated that the particle number density was in the range of 1–5 particles/mm$^3$. In some regions of pulverized coal flames, number densities of coal dust particles can be an order of magnitude higher than these values. Will your results be applicable to more highly loaded systems? Is it possible that the clouds around particles will interact, altering the behavior you have observed?

Author's Reply. We can adjust our experimental apparatus to give particle number densities in the range of 0.05 to 5 particles/mm$^3$, and the data presented here were obtained at densities in the range of 1–5 particles/mm$^3$.

Using data supplied to us by Babcock and Wilcox, we have calculated full scale burner coal feedpipe number densities in the range 0.5 to 5 particles/mm$^3$. In practical pulverized coal flames the particle number density is considerably less than the feedpipe density due to dilution with secondary air and with backmixed combustion products. Thus our experimental conditions do cover even the densest regions of practical pulverized coal flames, and under these conditions we do not observe significant interactions among the clouds that form around individual particles. Turbulent mixing in practical systems may well lead to enhanced mixing of the long stringy tails of soot-like material, but we do not expect this to significantly alter the elements of the soot formation phenomena reported here.