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Observation of the Behavior of Coal Particles During Thermal Decomposition

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This paper reports on the observed behavior of coal particles during thermal decomposition. The data presented are the first from a study initiated to address both the physical and chemical behavior of pulverized coal from the time of initial heating through the evolution of soot particulate. In the present study, pulverized (high volatile bituminous) coal was injected through a slit centered in a methane-air flat flame burner, and high resolution holography was employed to record the evolution of volatiles and the structure of soot particulate.

Volatiles were observed to evolve in a variety of shapes that range from individual jets to uniformly distributed clouds. Coal particle fragments and/or incipient soot nodules (~ 3 micron) were found to be present within the volatile gases during the evolution. Further from the burner, stringlike soot particles approaching 1600 microns in length were observed.

INTRODUCTION

The direct observation of reacting coal particles could provide valuable insight into fundamental processes associated with pulverized coal combustion and pollutant formation. Such a detailed understanding is required for the development of physical and theoretical models that could eventually lead to the development of advanced pollution control techniques.

The objective of the present study was to observe individual coal particle behavior during thermal decomposition. Techniques available for such observations include photography and holography. Photography is convenient only when

particles are known to exist in a given plane of focus, a condition that occurs, for example, when the particles are stationary or when the number density is extremely high. In reacting flows, these conditions seldom if ever exist. In contrast to photographic techniques, holography has the distinct advantage of allowing particles to be imaged in a dynamic field. As a result, holography was selected for the present study.

The following is a description of the combustion and holographic systems employed, together with a presentation of the results and a discussion of the basic coal particle combustion behavior observed. These results represent the first in a study of pulverized coal particle behavior during thermal decomposition.

EXPERIMENT

Combustion System

Coal particles carried by air were injected through a narrow (1.6 mm) slot into a flat, methane-air flame (Fig. 1). The burner consisted of a 13-cm sintered metal disk, and neither the burner nor the supporting flame was enclosed. The flat flame was operated near methane stoichiometry with a cold face velocity of approximately 30 cm/sec. The injection velocity of the coal was approximately 5 m/sec. The coal used for this study was a high volatile bituminous Utah coal. The samples were pulverized and repeatedly sieved through a 200 mesh screen until microscopic analysis indicated that a negligible fraction of fine particulate remained. The size range of the particles injected was approximately 75 to 100 μm . An auger feeder was used to control the feed rate of the prepared coal at about 70 gm/min. It is estimated that the coal experienced an initial heating rate of 10^5 to 10^6 $^\circ\text{K}/\text{sec}$.

Holography System

Holography has been applied to the study of several types of combustion with varying degrees of success (e.g., Refs. [1], [2], [3]). One of the principal problems is loss of resolution caused by imaging through the turbid and variable density medium normally associated with combustion. In

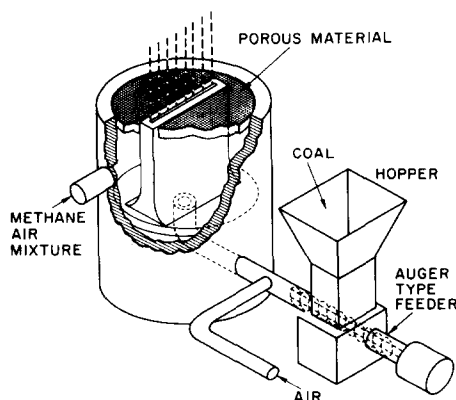


Fig. 1. Combustion system.

addition, resolution of particles is typically limited to diameters in excess of 50 μm . By application in the present study of special optical and mechanical techniques (described in more detail in Ref. [4]), coal particles in a reacting system were successfully observed down to a size resolution of 3 microns. High resolution was achieved by (1) magnifying with high quality lenses before recording, (2) using near image plane holography to relax the hologram requirements further, and (3) precisely aligning the hologram during reconstruction.

A schematic of the holocamera is presented in Fig. 2. The viewing volume recorded on each hologram was 2.54 cm (1 in.) in diameter and roughly 2.54 cm (1 in.) in depth.

EXPERIMENTAL RESULTS

Experimental results are presented for two locations in the flame. Results are shown in Fig. 3 for an area near the burner and in Fig. 4 for an area removed from the burner by approximately 5 cm.

Close to the Burner

Close to the burner (Fig. 3), particles are observed to be surrounded by clouds of devolatilization products. As seen, a variety of shapes occur that range from jets (e.g., Fig. 3(c)) to uniformly distributed clouds (e.g., Figs. 3(b), (d), (f)). A few of the forms are dramatic in structure (e.g., Figs. 3(e), (g)), indicating a strong explosionlike or complex soot formation process. It is noteworthy that evidence of devolatilization in Fig. 3(a) is bounded within a discernible horizontal band that represents a time differential of approximately 10 ms.

The clouds are found to contain numerous small particles, many of which are smaller than the system resolution. However, many clearly defined particles are seen within the resolved size range down to a few microns. These particles may be fragments blown off the parent particle by the violent devolatilization process or incipient nodules of soot. In view of events observed later in the flame (Fig. 4), the latter is highly probable.

Figure 3 is an example of a double-pulse image. The laser is pulsed in rapid succession (in this case,

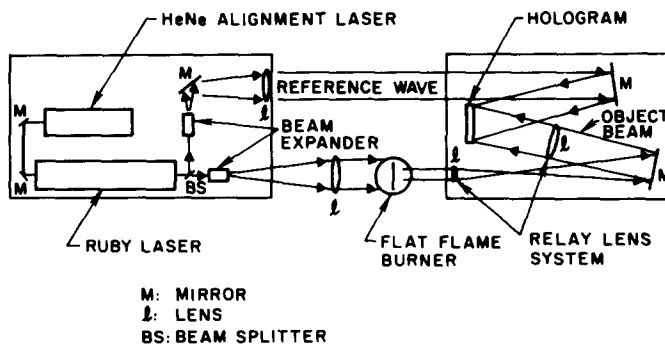


Fig. 2. Holography recording system.

with a time interval of 150 microseconds). As a result, two images are captured on the same hologram. For particles that can be separately identified in both images, information on particle dynamics can be assessed. Because the field is three dimensional, the identification of the same particle in both images is difficult and may be impossible in many cases. However, an example of the dynamics of one particle can be observed in Fig. 3(b). The displacement time information suggests a velocity of approximately 3 m/sec, which is reasonable considering the deceleration that occurs from the time of injection due to particle drag and spreading.

Removed from the Burner

At a position removed from the burner (Fig. 4), a variety of particle shapes are observed. Many particles are shown to be large in comparison to both the raw coal particles injection into the flame and the particle sizes observed close to the burner. The unusually long, stringlike structures (Figs. 4(b), (e)) are especially impressive. Note that one photographed particle (Fig. 4(e)), if continuous, exceeds 1600 microns in length. The size and shape of particles in this region suggest that many of them are soot particles; a conclusion that coincides with visual observations made of luminosity and particulate emission at this location in the flame. It is also of interest to note that all the stringlike structures are generally aligned with the direction of the flow. The smaller particles observed are more consistent in size with particles observed closer to the burner and are likely char.

Figure 4 is an example of holographic interferometry in which a second exposure is made seconds (in this case, 30 seconds) after the first exposure. An interference pattern is produced as a result of some geometrical or density perturbation in the system. A slight change in flame characteristics or a small movement in either the optical or experimental system is sufficient.

The advantage of holographic interferometry is the enhancement to the particle flow visualization and the identification of density variation. In the dark bands of the interferogram, white, black, and gray images can be observed. One explanation for the particles that appear gray in the dark band (e.g., Fig. 4(c)) is that they are transparent. The white images are probably particles present during one of the two exposures that have been rendered white by the additive exposure associated with the interference pattern. A remote possibility is that some of the white images are gaseous pockets. In Fig. 4(g), for example, an image is shown that suggests the presence of a gas pocket surrounding two char particles. (The example is located outside the boundary of Fig. 4(a), approximately 5 mm horizontally from the top left corner.) The ability to resolve pockets of variable density gaseous media has yet to be established.

SUMMARY

The present study, undertaken to observe the behavior of individual reacting coal particles, demonstrated that observation of coal particles during thermal decomposition can provide valuable insight

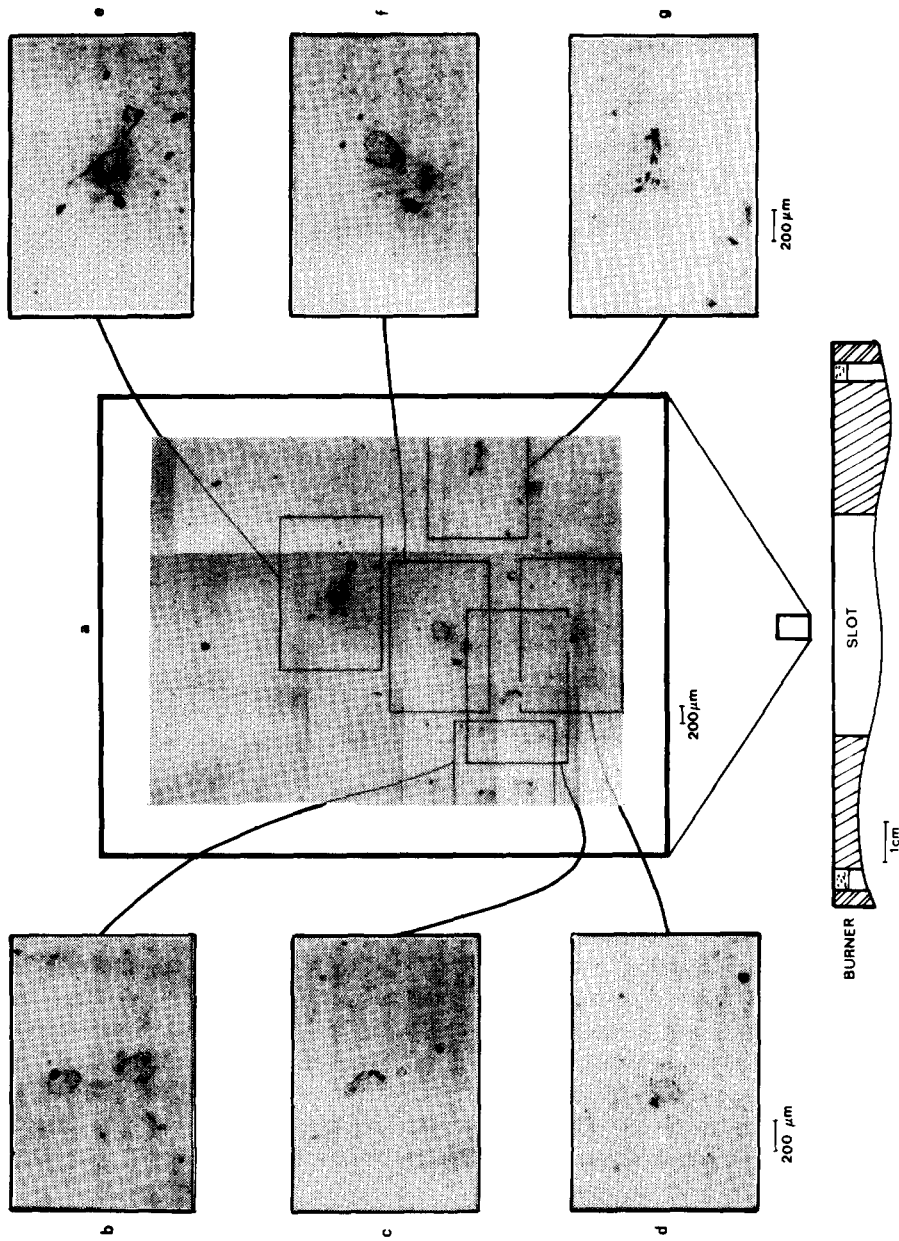


Fig. 3. Experimental results—close to burner.

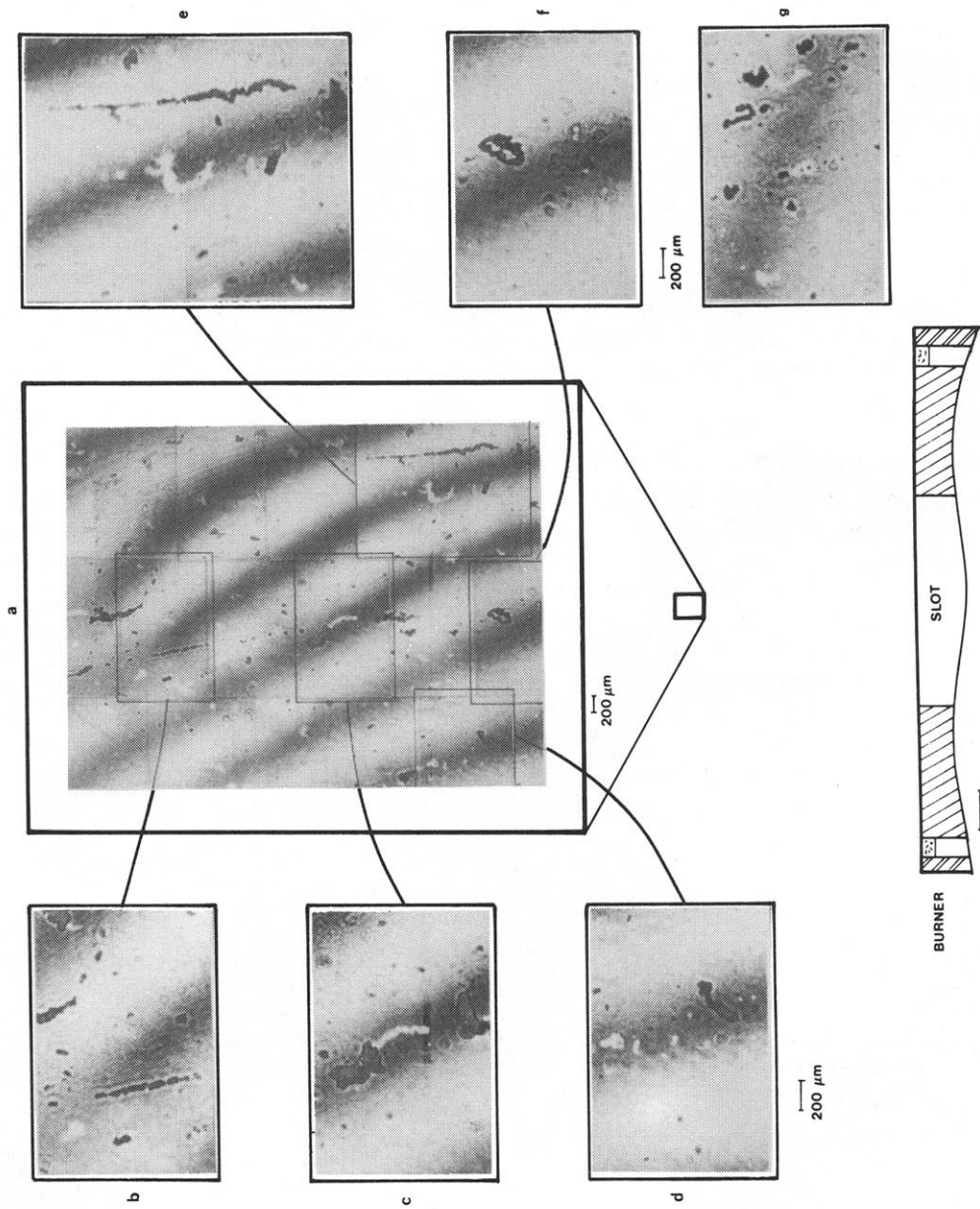


Fig. 4. Experimental results—removed from burner.

into the fundamental processes associated with pulverized coal combustion. Devolatilization clouds were observed early in the flame, and soot particles were observed late in the flame. Knowledge was also acquired concerning volatile cloud formation and structure and soot shape and size. In addition, double-pulse holography was shown to provide instructive dynamic information, while holographic interferometry demonstrated promise for enhanced flow and particle visualization.

The limited number of events observed in this preliminary assessment probably do not encompass the many that may be amenable to observation, nor do they provide sufficient information to draw substantive conclusions regarding the fundamental questions associated with coal particle behavior. Examples of questions amenable to further analyses include:

- The time-resolved changes in particle structure (volatile cloud evolution, cenosphere production, particle fracturization) during thermal decomposition.
- The mechanics of volatile cloud release, mixing, and burning.
- The correspondences, if any, between the physical behavior and the ultimate emission of soot, NO_x , SO_2 , ash, and their precursors.
- The effect of controllable parameters (e.g., fuel type, size, heating rate, volatile environment, temperature, stoichiometry) on the physical behavior and pollutant formation.

- The mechanics of soot formation.
- The mechanics of ash formation.

These questions are at present the subject of inquiry in an experiment that has been designed to explore the parametric variation required.

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