QUARTERLY PROGRESS REPORT

Title: Experimental Studies on Group Ignition
of a Cloud of Coal Particles

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OVERVIEW

Objectives for February 16, 1990 to May 15, 1990

1. Since an invitation was received from Professor Chigier, Editor Prog. Energy and Comb. Sc., for an article in the area of interactive combustion, efforts will be directed in collecting the literature on the interaction combustion of a cloud of drops and a cloud of coal particles.
2. Since Mr. Miguel Ruiz, a MS student has graduated in December, 1989 efforts will be directed in recruiting another student. This period will be used in writing the review paper.
3. Write the papers for presentation at Combustion Institute Meeting, Central States Section, May 1990.

Activities during February 16, 1990 to May 15, 1990

1. A rough draft of Part I of review paper dealing with interactive combustion processes dealing with liquid drop clouds has been completed.
2. A new MS student has been assigned to the project. The laboratory has been moved to a larger building for the exclusive use of combustion research.
3. Two papers have been submitted to the Combustion Institute Meeting. The most significant finding of group combustion model is the discovery of two propagating flames: one propagating into pre-mixed volatiles and air in the cloud and the second, a diffusion flame, established outside the cloud. This double flame is a characteristic of combustion of partially gasifying solids like coal. (See enclosed group combustion paper)
4. A two color pyrometer and a data acquisition system has been purchased.

Objectives for May 16, 1990 to August 15, 1990

1. Request for no extension of the project to August 31, 1991.
2. Complete Part II of review article on interactive combustion process dealing with coal particle clouds.
3. Install and calibrate the two color pyrometer systems for measuring the particle temperatures.
4. Purge the laminar flow reactor facility installed in the new combustion laboratory. Initiate the char ignition experiments.
5. Hire a new student to deal with the two color pyrometry.

GROUP COMBUSTION OF A CLOUD OF COAL PARTICLES

by

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(to be submitted for publication)

1. INTRODUCTION

A isolated fuel droplet burning in air has its own envelope flame. If another droplet is brought within close proximity of the first then the burning characteristics of the first drop changes due to interactions between the drops. This is the simplest example of interactive or group combustion. Most practical applications involve sprays, in which a large number of drops burn collectively as a group and droplet interactions are expected to have a significant effect on the combustion characteristics. Although the combustion characteristics of isolated droplets is well known, they are not applicable to group combustion without the use of correction factor. Thus it is imperative that the effect of drop interactions on the combustion characteristics of the spray be understood. Group combustion theory has evolved in order to predict these effects.

While droplet evaporation is a purely physical process, pulverized coal particles pyrolyse releasing combustible gases to the surroundings. The carbonaceous residue can undergo heterogeneous reactions with O_2 to CO and CO_2 . Thus coal can ignite in the gas phase (homogeneous ignition) or at the particle surface (heterogeneous ignition). Studies show that isolated particles ignite and burn heterogeneously [Chen et al., 1984; Howard et al., 1967], while clouds of coal particles ignite homogeneously or heterogeneously depending on the particle number density [Ruiz et al., 1989, Ryan and Annamalai].

For an initially cold cloud of coal particles, homogeneous ignition is shown to occur outside the cloud where the temperature is high [Ryan, 1988]. Once ignited, the volatiles in the gas phase form a diffusion flame which is maintained by volatiles released from the cloud. After some period, the volatile release rate can no longer support the flame outside the cloud and the flame moves toward the cloud. Once all the volatiles are burnt, the char burns at a rate controlled by the rate of oxygen diffusion to the cloud, rather than at a rate controlled by diffusion from adjacent regions. An average combustion rate is defined as the ratio of the cloud mass loss rate to the total number of the particles in the cloud.

This paper presents results for cloud mass fraction time history. Detailed flame structure profiles are also presented at various times during the combustion process.

2. RELEVANCE

When a pulverized fuel spray is injected into a boiler burner, the fuel spray rolls up in the shear layer to form eddies which entrain a cluster, which can then burn as a group. As an illustration, a figure from Chigier is reproduced in Figure 1 which illustrates the structure of a large eddy in a gas diffusion flame. The gaseous fuel region could be replaced by cold fuel particles with the cold gas immediately adjacent to the particles. The detached fuel rich regime burns when brought in contact with high temperature air rich regions. These clusters contain particles with different equivalence ratios. In order to

illustrate the combustion of such a cluster, a simplified combustion model is proposed for a cloud of particles.

3. MODEL

A spherical 1 cm radius cloud of 100 μm diameter particles was used as simple model (Fig. 2) and is assumed to be representative of a cluster of coal particles in a boiler burner. If this cloud is placed in a hot furnace, a thermal wave propagates from the ambience into the cloud. The bulk gas temperature increases which in turn supplies heat to the particles. When the temperature of the particles reaches the pyrolysis level, thermal decomposition of coal occurs releasing volatiles. The volatiles diffuse into the bulk gas zone establishing a mixture of volatiles and oxygen in the bulk gas. The volatiles then undergo rapid gas phase oxidation reactions resulting in the formation of a flammable mixture and ignition if the local gas phase temperature is high enough. If the cloud is dilute, a flammable mixture may not be formed which may result in heterogeneous ignition. Thus the ignition mode may be either homogeneous or heterogeneous depending upon the denseness of the cloud.

3.1. Assumptions

The assumptions are briefly summarized below. A more detailed accounting of the assumptions and justification are given elsewhere [Annamalai et al., 1988] (i.) Spherical symmetry exists, (ii.) $\rho D = \text{constant}$, (iii.) The particles act as point heat and mass sources,

(iv.) The mass heat generated from the particles is distributed rapidly in the interstitial space between the point sources.* (v.) Pyrolysis occurs volumetrically with no swelling, while heterogeneous reactions occur at the external surfaces of the coal particles. Hence during pyrolysis, the density decreases at constant diameter and for heterogeneous reactions, the particle shrinks at constant density, (vi.) Combustion is complete, (vii.) All gas phase chemical reactions for volatiles and CO occur by a single step global reaction. The reactions included in the present analysis are as follows:

a.) Heterogeneous Reaction

b.) Pyrolysis via Competing Reaction

$$\alpha_I \text{ Volatiles-I} + (1-\alpha_I)C \quad (II-1)$$

Coal

$$\alpha_{II} \text{ Volatiles-II} + (1-\alpha_{II})C \quad (II-2)$$

where $\alpha_I \simeq 2\alpha_{II}$ [Wall, 1987]

c.) Homogeneous Reactions

* Under dense cloud conditions the interparticle spacing (l/a) is very small and hence such an assumption may be justified. However, under dilute conditions, (l/a) is large. Using a dimensional order of magnitude analysis, it can be shown if $l/a \ll 200$, then the assumption of instantaneous diffusion is justified for $100 \mu\text{m}$ diameter particles.

3.2. Numerical Method

An explicit forward difference scheme is used to march in time. The gas phase conservation equations are solved using a central difference scheme for the diffusive terms and a upwind scheme for the convective terms. Difficulties in the numerical model scheme were encountered once a diffusion flame was formed since the reaction rate for the current time step was determined using the temperature and gas phase composition of the previous time step (Fig. 3, point A). The use of this reaction rate over a finite time step results in negative values of gas phase mass fractions at the end of the current time step (Fig. 3, point B). This difficulty was resolved by determining the maximum reaction rate possible which still results in positive values of species mass fractions at the end of the time step (Fig. 3, point C). If this value reaction rate is less than the value of reaction rate determined using temperature and species mass fractions, then some fraction (usually 0.99*) of the maximum possible reaction rate is used in solving for species mass fraction.

4. RESULTS AND DISCUSSION

* The value of fraction used is unimportant since this is a diffusion flame and as such is independent of the actual kinetics

Figure 4 shows the flame radius as a function of time. The flame is said to be located at the position where a peak in the gas phase temperature occurs and ignition is said to have occurred when this peak is first observed. Ignition occurs outside the cloud (location 1) due to the formation of a flammable mixture of released volatiles in the hot ambience surrounding the cloud. Figure 5 shows the flame structure at ignition. The volatiles concentration outside the cloud is relatively low and since the temperature is high and oxygen is plentiful, the flame moves toward the cloud in search of volatiles. By the time the flame has reached the cloud, a noticeable peak in temperature and carbon dioxide has formed (Figure 6). The flame now anchors itself at the cloud surface, consuming volatiles and oxygen until the oxygen at the cloud surface has been completely consumed (Figure 7). Two flames are now formed, one which moves inward and the other outward (Figure 8). The outer flame is a pure diffusion flame, while the inner flame is a combination premixed/diffusion flame. The inward propagating flame supplies heat to the particles for pyrolysis, resulting in an extremely fuel rich region between the flames (Figure 9). Once the outer flame reaches the maximum distance from the cloud, the inner flame has almost consumed all the oxygen in the cloud (Figure 10). At 249 ms (location 7), the inner flame has completely extinguished, two peaks are no longer observed and the volatile mass fraction at the cloud center has reached about 0.40 (Figure 11). A flame is sustained at this radius until the diffusion of volatiles slows at which time the flame begins to propagate

inward (Figure 12). Finally, the volatile concentration becomes low enough to allow the flame to reach the cloud surface and heterogeneous oxidation of the remaining char ensues (Figure 13).

Figure 14 shows the cloud mass fraction as time varies. Initially, the mass loss rate is slow and the curve is nearly horizontal. Once the flame reaches the cloud surface, the mass loss rate increases greatly as a result of increased pyrolysis. During the next 20 ms the cloud completely pyrolyses. This time interval corresponds to the time required for the inner flame to propagate from the cloud surface to the center of the cloud. Once pyrolysis is complete, the cloud mass loss rate becomes almost zero since there is no oxygen within the cloud to consume the remaining char. Thus the cloud mass fraction remains constant until the outer flame consumes all the volatiles outside the cloud allowing oxygen to penetrate the cloud surface ($t \approx 530$ ms). The combustion of the remaining char particles is controlled by the rate of oxygen diffusion to the cloud, rather than by the single particle combustion rate.

Assuming a QS combustion model for a spherical cloud of char particles under sheath combustion conditions is approximately valid in this region, the sheath combustion rate is given as [Annamalai and Ramalingam, 1987]

$$\dot{m}_{s,c} = 4\pi\rho DR_c(t)\ln(1 + B) \quad (1)$$

where

$$B = 1 + \frac{Y_{O_2,\infty}}{\nu_2} \quad (2)$$

$$\nu_2 = \frac{W_{O_2}}{W_C} \quad (3)$$

Equations (2) and (3) are valid only if the final products are CO_2 and the Boudouard reaction is insignificant. With $R_c = 0.01$ m, $\rho D = 0.5 \times 10^{-4}$ kg/s, $\nu_2 = 2.667$, and $Y_{O_2,\infty} = 0.23$, the cloud burning rate is given as 0.52×10^{-6} while the computer output gives the burning rate as 0.47 to 0.53×10^{-6} kg/s. As the cloud burns, the cloud radius decreases and as such the cloud burning rate decreases as predicted by the sheath combustion rate. It also should be noted that eq. (1) assumes a steady state oxygen profile surrounding the cloud, however the initial depletion of oxygen due to combustion of volatiles coupled with the receding cloud radius will result in a decreased burning rate.

It is apparent that while an individual $100 \mu\text{m}$ diameter char particle can burn in approximately 230 ms ($t_b \approx d_0^2/\alpha_b$, $\alpha_b = 8\rho D \ln(1+B)/\rho_p$, $\rho_p = 780$ kg/m³), a 1 cm radius cluster of $100 \mu\text{m}$ diameter particles with a number density of 0.8×10^9 particles/m³, will burn in about 1 s ($t_b \approx R_{c,0}/\alpha_b$, $\alpha_b = 8\rho D \ln(1+B)/\rho_{cl}$, $\rho_{cl} = \rho_p \sigma_{fuel}$, $\sigma_{fuel} = \text{fuel volume fraction} = n(\pi d_p^3/6) = 0.42 \times 10^{-4}$, $\rho_{cl} = 0.33$ kg/m³, $\alpha_b = 10^{-4}$ m²/s). If the cluster size is reduced and/or if the transport coefficient ρD is enhanced by micromixing, then the combustion time could be reduced. It should be cautioned that the

real physical process is much more complex than the one modeled here.

5. SUMMARY

While the combustion characteristics of a single coal particle are well known, most practical applications of coal combustion involve a large number of particles burning collectively as a group. A group combustion model has been developed which models the transient combustion of a spherical coal cloud. This model predicts ignition of a homogeneous mixture of volatiles and oxygen outside the cloud. The flame then moves to the cloud surface, where it anchors itself until all of the oxygen at the cloud surface is consumed. Two concentric flames are then formed, an outward propagating diffusion flame and an inward propagating premixed/diffusion flame which supplies heat to the particles for pyrolysis. Once the inner flame has consumed all the oxygen in the cloud, pyrolysis is complete and the outer flame consumes the released volatiles. As the volatiles are consumed, the flame approaches the cloud surface. Once all the volatiles have been consumed, the remaining char in the cloud burns at rate controlled by the rate of oxygen diffusion to the cloud.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

- Annamalai, K., and Ramlingam, S. (1987) "Distinctive Burning Characteristics of Carbon Particles," *Combustion and Flame* Vol. 70, pp. 307-332.
- Annamalai, K., Ramalingam, S.C., and Ryan, W.R. (1988b) "Group Combustion of Coal Particles," Annual Report No. 2, PETC/DOE, Pittsburgh, PA.
- Chen M.R., Fan, L.S., and Essenhigh, R.H. (1984) "Prediction and Measurement of Ignition Temperature of Coal Particles," *Twentieth Symposium (International) on Combustion*, pp. 1513-1519.
- Howard, J.B., and Essenhigh, R.H. (1967) "Pyrolysis of Coal Particles in Pulverized Fuel Flames," *Industrial Engineering Chemical Process Design and Development*, 6, pp. 74-84.
- Wall, T.F., Principles of Combustion Engineering for Boilers, Edited by C.K. Law, Chap. 3, Academic Press, NY (1987).

Fig. 1 Turbulent Eddy in a Gas Diffusion Flame (Chigier, 1981)

Fig. 2. MODEL

Fig. 3. Source Correction Method

Generalized Conservation Equation

$$\rho^* \frac{\partial \psi}{\partial \tau} - \alpha \xi^4 \frac{\partial \psi}{\partial \xi} - \xi^4 \frac{\partial^2 \psi}{\partial \xi^2} = w_p + w_{ch} - w_m \psi$$

Equation for Maximum Consumption Rate

$$w_{ch,max} = \rho^* \frac{\psi_A}{\Delta \tau} - \alpha \xi^4 \frac{\partial \psi}{\partial \xi} - \xi^4 \frac{\partial^2 \psi}{\partial \xi^2} - w_p + w_m \psi$$

Correction Factor

$$\eta = \text{MIN} \left(1.0, \frac{w_{ch,max}}{w_{ch}} \right)$$

Fig. 4

Flame Radius Time History

Fig. 5

Flame Structure at Ignition

Fig. 6.

Flame Structure at Location 2

Fig. 7

Flame Structure at Location 3

Fig. 8.

Flame Structure at Location 4

Fig. 9.

Flame Structure at Location 5

Fig. 10

Flame Structure at Location 6

Fig. 11

Flame Structure at Location 7

Flame Structure at Location 8

Fig. 12

Flame Structure at Location 9

Flame Structure at Location 10

Fig. 13.

Fig. 14

Cloud Mass Fraction Time History

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