A STUDY OF THE BURNING VELOCITY OF LAMINAR COAL DUST FLAMES

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Conducted in
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STUDENT OF THE BURNING VELOCITY
OF LAMINAR COAL DUST FLAMES

by
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STATEMENT OF TRANSMITTAL

Special Report SR-36 transmitted herewith has been prepared by the Coal Research Section of the Mineral Industries Experiment Station. Each of the Special Reports presents the results of a phase of one of the research projects supported by the Pennsylvania Coal Research Board or a technical discussion of related research. It is intended to present all of the important results of the Coal Board research in Special Reports, although some of the results may already have been presented in progress reports. The following is a list of Special Research Reports issued previously.

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The Preparation Characteristics of the Bituminous Coal Reserves in Pennsylvania with Special Emphasis on Sulfur Reduction

October 31, 1962

M.E. Bell, Director
M.I. Experiment Station
SUMMATION OF RESULTS

The ever-increasing importance of pulverized coal combustion points to the need for basic information on pulverized coal flames, in order to build a fund of knowledge that will enable coal technologists to meet competition from other fuels.

The present work is a study of the burning velocities of coal dust suspensions. The work has been carried out on small flames on a tube burner, under conditions of laminar flow. Most of the measurements have involved one selected bituminous coal, plus blends of this coal with anthracite.

Burning rates have been measured over a wide range of coal dust concentrations, using supporting atmospheres slightly enriched in oxygen. The burning rate exhibits a maximum at a composition lying between stoichiometric for the total coal and stoichiometric for the coal volatiles. An analysis of the dependence of burning rate on the flame temperature shows that both radiative and conductive heat transfer are important in these small, laminar flames. Because conductive transfer is important, combustion of the volatiles, which gives rise to large conductive transfer in the flame front, is a significant factor in determining the burning rate. As a result, blending of bituminous coal with anthracite always decreases the burning rate. In large flames, this should not occur because radiant transfer will dominate.
ACKNOWLEDGEMENT

The authors acknowledge the assistance of Dr. F. J. Vastola, who designed the thyratron trigger circuit, and Mr. B. E. Knox, who measured the response time of the thyratron circuit-solenoid valve system.

They are also indebted to Dr. Hans Cassel of the U.S. Bureau of Mines for helpful discussions and the loan of a prototype of the dust dispersion device.

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INTRODUCTION

PURPOSE

The combustion of solids in suspension has become the subject of increasing interest in recent years. Although pulverized coal has been burned in furnaces for more than half a century, the research thus stimulated has been mainly of an applied nature. Recently, however, a need for more fundamental information on combustion in suspension has been generated by the more stringent requirements in pulverized fuel furnaces and the prospects of using solid fuels in gas turbines and ramjets. The search for a more basic understanding of these processes is hampered by the lack of experimental data to guide the theoretical approaches.

The current work was undertaken to help in correcting this shortage. During the investigations of this relatively unstudied chemical system, several exploratory experiments have been performed which may indicate fruitful lines for future research.

HISTORICAL REVIEW

Combustion Studies

In order to obtain fundamental information on physical or chemical phenomena, experimentation should be carried out on as simplified a system as possible, one in which important parameters can be controlled. Surveys of the work in dust cloud combustion show that such an approach has rarely been the case (for exceptions see below and refs. 4, 5, and 6).
Stationary laminar flames on laboratory-scale burners appear to give a reasonably simplified system. The system possesses an additional appeal because of the vast amount of gaseous combustion research done on these flames. Experimental studies with this approach are extremely rare, however, probably because of the great difficulty in stabilizing the dust flames. Hence most of the work to date has used some auxiliary means to attain stability (e.g., pilot flames, addition of combustible gases, or hot furnace walls).

V.D. Long employed an annular coal gas-air (pilot) flame to stabilize laminar flames of high-volatile (34% V.M.) coal dust-air mixtures moving either upward or downward. For dilute mixtures (less than 120 mg./l.) a heated furnace was used to promote stability. Photographs of the flames showed an inner cone with a sharp flame front from which burning velocity measurements were made using a total area method. The burning velocity showed a rise from a low value at the leanest concentrations to a plateau at approximately 220 mg./l. The maximum burning velocity decreased with increasing particle size. With 11 micron (average diameter) particles the maximum burning velocity was 9 cm./sec. while for 45 micron particles it was 5 cm./sec., for downward moving streams from nozzles. While his data are valuable, the leveling-off of the burning velocity curve is unexplained and the effect of the pilot flame on the behavior of the system is open to question.

Another means of maintaining stable coal dust-air flames was devised by H. Hattori. Using a diffusion flame of acetylene as
a constant ignition source in the middle of the coal dust stream, he produced a flame with an inverted cone shape. The angle of this cone was then used to calculate burning velocities. For a high volatile (42.4% V. M.) coal, he found burning velocities that increased (from 20 to 45 cm./sec. at maximum) as the oxygen percentage increased (from 21% to 35%). His burning velocity data show a sharp increase with decreasing particle size and they go through a maximum for air mixtures at about 625 mg./l. Little significance can be attached to this concentration value because of the stoichiometry changes brought about by the acetylene diffusion flame. (Acetylene flow rates were normally 30% of the total volume flow rate.) The use of this ignition source would seem to make the results usable only on a qualitative basis for comparisons.

Ghosh et al. succeeded in stabilizing coal dust flames on a burner port by increasing the oxygen content of the mixture for minus 200 mesh and 100 x 160 mesh particles. The flames that they produced showed no inner cones, thus obviating any burning velocity measurements; however, they were able to obtain data on the flow velocity at the mouth of their burner for which the flame was stable, and on the related ranges of coal concentration. Their data agree with those of previous investigators in showing a decrease in the coal concentration necessary for stable flame formation as the particle size decreases. They also show an increase in the minimal oxygen content necessary for stability as the volatile matter in the coal decreases. A reduction in volatile content from 37% to
21% required an increase in oxygen from 60% to 100% of the gas in the mixture.

Bunsen flames of aluminum and dextrin dusts (both minus 40 microns) and flat flames of aluminum and graphite dusts (both minus 6 microns) were stabilized by Cassel and co-workers. The Bunsen flames showed inner cones and had burning velocities that increased with decreasing particle size and increasing dust concentration on the lean side of stoichiometric. With the flat flames, the simple geometry of the system permitted them to estimate the radiative contribution to the heat transfer. For graphite dust burning in oxygen the contribution was about 60%, while for aluminum dust burning in air it was about 35%, which is in keeping with the absorptivities of the two materials.

Several investigators (e.g., references 11, 12, 13) have studied the burning times of single particles, either free falling in furnaces or captive on rods. The consensus of these workers has been that the burning time for combustible particles varies directly with the square of the initial diameter to a very good approximation. While there is some question as to the application of these data to actual flames they can be helpful as a relative measure of the true burning time.

The theoretical studies of dust cloud combustion may be divided into two classes: first, those that consider radiative heat transfer to be so dominant in the combustion process that conduction may be neglected; and second, those that consider both radiation and conduction to be important. Of the first type, the basic
equations, originally formulated by Nusselt, have been modified and solved analytically by Essenhigh and Csaba. Their resultant equation for the burning velocity of coal dust flames is

\[
S_u = \frac{I_f (1 - e^{-mt_i})}{(T_i - T_o) (D_o C_d + \rho_0 C_p)}
\]

where

- \( S_u \) = burning velocity
- \( I_f \) = radiation intensity at the flame front
- \( m \) = radiation time-attenuation coefficient
- \( t_i \) = ignition time
- \( T_i \) = ignition temperature
- \( T_o \) = initial temperature
- \( D_o \) = dust cloud concentration at input
- \( C_d \) = specific heat of dust
- \( C_p \) = specific heat of gas at constant pressure
- \( \rho_0 \) = air density at input

The distinctive features of this approach are the assumptions that conductive heat transfer is negligible, that a fixed ignition temperature exists which is equal to the coal decomposition temperature (devolatilization temperature), and that the flame is a grey body of average temperature \( T_f \). This treatment was developed primarily for large, optically thick flames. Essenhigh and Csaba have expressed reservations about its application to smaller flames.

The other approach to a theoretical description of dust cloud combustion assumes that both radiation and conduction are important. Cassel has modified the Mallard-Le Chatelier burning velocity equation to include radiation. The resultant equation is
similar to Essenhigh and Csaba's, but with a term for conduction added to the numerator of the right hand side. As presented, this approach can not make quantitative predictions but it is capable of indicating relative effects of the various parameters. It takes the following form:

\[
S_u = \frac{\lambda \left( \frac{(T_f-T_i)}{b} \right) + b \omega \sigma \xi (T_f^4 - T_o^4)}{(C_p + C_d w) (T_i - T_o)}
\]

where \( S_u \) = burning velocity

\( \lambda \) = coefficient of heat conductivity

\( T_o, T_f, T_i \) = temperatures of the unburned and burned masses and of ignition

\( \sigma \) = emissivity of the particle surfaces (including the S-B constant)

\( \xi \) = a correction factor >1 which accounts for radiation of glowing combustion products (gas and solid)

\( F \) = a geometrical view factor

\( b \) = the thickness of the burning zone

\( C_p \) = specific heat of the gas

\( \rho \) = density of the gas

\( C_d \) = specific heat of the dust

\( \rho_d \) = density of dust

\( w \) = concentration of dust

\( r \) = average particle radius

While relationships have been observed (e.g., reference 9) between combustion parameters and volatile matter content of coals,
the theoretical treatments have generally avoided this aspect. (In
the radiation theory it would be considered only as it affected the
flame temperature.) Most theoretical studies (e.g., reference 15)
of the combustion of coal have considered the reaction to be hetero-
geous and have assumed that carbon was a good approximation to
coal.

While there are situations where the combustion of coal is
a purely heterogeneous process, such as the combustion of residues
or very low volatile coals (anthracite), and perhaps for conditions
where there is very rapid heating (dust explosions), it is certainly
not generally true. Prior combustion of volatile matter has been
established for several cases, especially for high volatile coals.
Long 16 has observed two distinct reaction zones in his flames and
attributes the first and more luminous zone to the very rapid com-
bustion of the volatile matter and the second and less luminous zone
to the protracted combustion of the coke residue. From this evi-
dence and the location of the maximum burning velocity almost mid-
way between stoichiometric for the whole coal and stoichiometric
for the volatile matter, Long suggests that laminar coal dust flames
are essentially gaseous flames through which the coke residue
passes and burns independently.

Generation and Handling of Dust Clouds

Dust clouds generated for combustion studies will have most
of the characteristics of normal gas clouds (for ordinary concentra-
tions the dust occupies less than 0.03 percent of the volume). They
are, however, inherently unstable. Particles may disappear by
sedimentation or diffusion to the walls of the containing vessel, while collisions resulting from Brownian motion and differential sedimentation lead to the continuous formation of aggregates which change the properties of the cloud.

There are several works available that review the properties and problems of dust clouds. Dallavalle’s monograph\(^1\) presents a great deal of information on fine particle technology and is especially directed to industrial applications. The Atomic Energy Commission has published a **Handbook on Aerosols**\(^2\) which gives a concise presentation of many of the physical properties of aerosols with special emphasis on air pollution problems. More recently, Green and Lane\(^3\) have summarized and analyzed much of the vast and scattered literature on this subject. A large part of their book is devoted to the physics and physical chemistry of fine particles in suspension.

Of the several types of apparatus designed to generate laminar dust clouds of very fine particle size (<10\(\mu\)m), the one that seems to be the most successful and versatile was designed by Cassel and co-workers\(^4\). The basic idea is that a gas jet impinges on a moving dust bed and the resultant cloud is formed in the base of the burner tube, thus conserving momentum for vertical flow and not dissipating it in expansion (cf. subsequent discussion and Figure 2).

The aggregation of particles has always been a problem in dust dispersion. While many of the possible causes have been studied, only the effect of surface moisture seems to be understood reasonably well. Wolf and Hohenleiter\(^5\) have shown that the
adhesion of coal dusts goes through a maximum at about 12% moisture and then decreases, which seems to correspond to the building up of a double layer of water molecules.

**STATEMENT OF PROBLEM**

The combustion of laminar dust flames has a great deal of intrinsic interest as a relatively unstudied phenomenon. This alone would constitute a purely academic reason for its investigation. There is, however, a more practical impetus. In order to improve industrial combustion techniques, an increased knowledge of the mechanism of combustion is required.

Measurements of the burning velocity of laminar coal dust flames have not been made except for cases where artificial means were used to sustain the flames. Since the rate of flame propagation is a basic parameter for combustion studies, it is exceedingly desirable to obtain values for it without the complicating presence of a constant external ignition source. Such measurements should be more suitable for testing the theoretical approaches and their assumptional bases.

This work has had its main objective the determination of the conditions for establishing laminar coal dust flames and the measurement of the burning velocities of these flames. Further, a study has been made of the conditions that determine the rate of flame propagation for clouds of high volatile coal dust and blends of the same dust with anthracite. Additional information has been obtained which may help to clarify the question as to the relative importance of conductive and radiative heat transfer in dust flames.
II

PROCEDURE OF THE INVESTIGATION

APPARATUS

A schematic diagram of the basic apparatus appears in Figure 1.

Gas Handling System

All gases used in this work were supplied in high pressure cylinders and their flow into the system was controlled by needle valves. The flow rates of the oxygen and nitrogen used to generate the dust cloud were metered by Matheson model 205 Universal Flowmeters. For the nitrogen (and occasionally air), a stainless steel float was used that gave a usable range of 1000 ± 75 cc./min. to 17,000 ± 175 cc./min. For the oxygen (and later methane), a glass float was used that provided a usable range of 700 ± 75 cc./min. to 7,500 ± 100 cc./min. The nitrogen used to surround the dust cloud was metered with a Matheson model 206 Universal Flowmeter using a stainless steel float. At a setting of 9.5 units (22,400 ± 400 cc./min.) the nitrogen stream maintained the cloud configuration and this setting was used throughout the course of the experiments. All the flowmeters were calibrated from data supplied by the manufacturer and subsequent checks against a dry test meter were satisfactory.

All of the gas lines in the system were of 1/4" copper tubing, and the connections were Swagelok compression type fittings. Pressure in the lines was measured by two Matheson no. 704 gauges.
The jets were mixed at a T in the line and then divided into two streams before entering the dust dispersion chamber.

Figure 1

SCHEMATIC DIAGRAM OF APPARATUS
The gases were mixed at a "T" in the line, and then divided into two streams before entering the dust dispersion chamber.

**Dust Dispersion Unit**

Dispersion of the dust was achieved by means of a unit at the bottom of the burner tube (Figure 2). The heart of the dust dispersion unit was a hypodermic needle (no. 22 or 20 gauge), through which the input gas stream passed at a pressure drop of about 20 psig. The exiting high velocity gases impinged on the dust bed, thus generating the dust dispersion. The dust reached the hypodermic needle through an opening cut in the base of the burner tube (the height of the opening was controlled by taping a piece of aluminum foil at the desired position). A constant supply of dust was kept moving to the dispersion chamber by the rotation of the brass container which enclosed the entire dispersion unit. The rotation rate of the container could be varied from 1.5 to 5.5 rpm. An emery paper lining was cemented to the bottom of the container to prevent the dust from slipping. A dust-tight seal between the rotating container and its stationary top was provided by greased bearing surfaces at their juncture.

In addition to the gas flowing through the hypodermic needle, another stream of gas flowed through a central dilution tube (B Figure 2). This stream was used to decrease the proportion of the gas used to disperse the dust, thus allowing the concentration to be varied. Regardless of the flow rate through the central tube, the pressure behind the hypodermic needle was normally maintained at 20 psig.
Burner Tube and Related Equipment

The dust cloud, thus generated, rose vertically through the burner tube (2 cm. I.D., 56 cm. length) which was tapped continuously by a 60 cycle electromagnetic vibrator. A preheat section for the top 22 cm. of the burner tube was made from a 2 cm. i.d. mullite tube wrapped with 1/8" Kanthal ribbon and covered with a thin coating of Sauereisen no. 7 cement. The temperature of the preheat section was measured by a thermocouple imbedded in the mullite tube. The thermocouple output was measured by means of a Rubicon Precision Potentiometer model no. 2745. Just below the preheat section, a 1 cm. section of Teflon was inserted as a fuse holder. In this section a strip of lead foil (3.5 cm. long and 0.15 cm. wide) was clamped across the center of the tube, oriented with the flat side parallel to the flow. The ends of the fuse were connected to a thyatron trigger circuit (Figure 3). When a flashback melted the fuse, the thyatron fired and actuated a Hoke solenoid valve (series 90) that permitted a stream of nitrogen to flow into the tube, upstream, and extinguish the flame. The reaction time of the circuit-valve system was measured on an oscilloscope. A micro-switch (normally closed) replaced the fuse for this measurement. When the switch was opened, the thyatron triggered an oscilloscope sweep and the solenoid valve opened. The gas flowed through the valve and impinged on a plunger soldered to an arm of an Astatic phonograph cartridge. The signal from the cartridge was picked up on the oscilloscope in a response time of about 5.5 milliseconds. This rapid response was necessary to prevent a flashback flame from
entering the dispersion chamber.

Surrounding the upper 30 cm. of the burner tube was a 5 cm. i.d. aluminum jacket through which flowed the auxiliary nitrogen stream (H Figure 4). This nitrogen was admitted at the bottom of the surrounding tube through two inlets which led into a packing of glass wool. From there, it flowed unrestricted to the top, where it was accelerated through a nozzle. The optimal rate of flow of this stream was determined visually, by varying the flow until the cylindrical configuration of the dust cloud was maintained for about 10 cm. above the port.

Unburned dust and combustion products were exhausted through a suction duct located about 15 cm. above the burner port.

In order to maintain a stable flame consistently for reasonable periods of time (i.e., 2 to 10 secs.), it was necessary to use a flame holding device (D Figure 4). Of the several types tried, the most successful was a brass ring with a conical cross section, where the apex of the cone was oriented downward toward the burner. It was normally located with its top 1.6 cm. above the burner port. The flat top of the ring generated a highly localized recirculation pattern above the ring as observed visually. It is thought that ignition took place in this relatively stagnant part of the cloud, thus providing a pilot flame which acted as a constant ignition source for the flame. This is similar to bluff body stabilization of turbulent flames. It was found that the stabilizer functioned best after it had been heated by the flames; therefore, it was customarily heated before igniting the flames. Resistance wire was wound around the
Figure 4

RADIANT IGNITION EQUIPMENT IN REGION OF BURNER PORT

A CARBON ARC LAMP
B RADIANT FLUX ATTENUATOR
C LENS
D FLAME STABILIZER RING
E THERMOCOUPLE PROBE
F PEN RECORDER
G BURNER TUBE
H AUXILIARY NITROGEN JACKET

Cross Section of Ring D

- 2.5 cm
- 1.8 cm
- 0.4 cm

HOOD

F

G

H

C

C

D

C

D

B

A
brass rod supporting the ring (insulated and covered by asbestos) permitting it to be heated to about 650°C. The temperature of the ring itself must have been considerably less than this, though it was not possible to measure it under the conditions of the experiments.

For several experiments with methane-air flames the top 38 cm. of the burner tube (including preheater, fuse and auxiliary nitrogen jacket) was replaced by a 1.7 cm. i.d. Pyrex tube of similar length.

The dust clouds used for all the burning velocity studies were ignited with an ordinary glass-blowing torch, burning natural gas-oxygen mixtures.

**Accessory Equipment**

Photographs of flames for burning velocity measurements were taken with a Speed Graphic camera using 2 1/4" x 3 1/4" Plus-X Pan film. A Wratten C5 filter (no. 47) was used for all dust-containing flames. The aperture setting and exposure time were f/4.5 and 1/25 sec. respectively. For low dust concentrations in methane-air flames were photographed, no filter was used, the lights in the room were turned off, and the exposure time was increased to 1/10 sec. Normal magnifications were 0.63 to 0.75.

Frustum measurements were made on enlarged images formed by a Spencer projector model MK. Normal magnifications were 9 to 15 times the photographed image. The top of the flame stabilizer was visible in all photographs. Two lines were drawn parallel to it on the projected image, designating the limits of the
frustum. The diameters of the top and bottom of the frustum were measured with a ruler to ± 0.05 cm.

In the ignition studies, motion pictures of the dust cloud were taken with a Bell and Howell Filmo 70, 16 mm. camera, using Plus-X film. Because of the brilliance of the flame it was necessary to use an aperture setting of f/16, even at 64 frames per second.

Dust cloud concentrations were determined by collecting the entire dust output for a known time. The sampling was made with a Pyrex bulb about 5 cm. in diameter, packed with glass wool, with 14 mm. diameter tubes sealed to openings at either end. One tube led to the suction pump; and the other was bent through an angle of about 100°, and then flared at the end for collecting the sample. The suction was supplied by a Millipore Filter Corporation vacuum-pressure pump. In the line between the pump and the sampling bulb there was a 2-inch diameter filter holder containing a Gelman Instrument Company type AM-1 filter. This filter was capable of collecting particles below 1 micron, but only on rare occasions (when the glass wool in the bulb was improperly packed) did any noticeable amount of dust accumulate. Sampling time was controlled by an Industrial Timer Corporation model P-4R interval timer which regulated the operating time of the suction pump.

The thermocouple probe was made from 40 gauge Pt-Pt 10% Rh wire, enclosed in two-hole mullite insulation (1/32 "O.D., holes 0.005"). The junction weld was made on a Burrell Kup-L-Weld thermocouple welder, but operated at 30 volts instead of the normal 110 volts to avoid burning out the thermocouple. In order to make
the horizontal positioning of the probe smooth and reproducible, it
was placed inside a telescoping section of an automobile radio anten-
na. Thus, when the outer tube of the antenna was secured, the inner
one could slide smoothly to and from the flame. The output from the
thermocouple was fed directly to a Minneapolis-Honeywell fast pen
recorder (1 second full scale). The recorder had a normal range
of 0-1 millivolts but this was adjusted by a voltage divider to 0-23.2
millivolts. In order to decrease the danger of catalytic reaction at
the thermocouple surface, it was necessary to apply a protective
coating. Silicon dioxide has been shown\textsuperscript{23} to be effective for such
a purpose. When the thermocouple was passed through a Bunsen
flame in which small amounts of hexamethylidisilazane were decom-
posed, a film of silicon dioxide was deposited on its surface. It
was found that thick coatings (about 0.02 mm.) were very brittle and
inclined to flake. Therefore, only very thin (barely visible) coat-
ings were used.

The optical system used to study radiant ignition consisted
of a condenser-type carbon arc lamp, a flux attenuator, three lenses,
and a radiometer to measure the flux (Figure 4). The carbon arc
lamp was a Peerless type 15 Hy-Candescent Arc Lamp. It normally
operated at 115 amps and 58 volts, the power being supplied by the
motor-generator of a Wilson Hornet, model BA 400, Arc Welder.
Radiant flux to the dust could was controlled by a sliding wedge at-
tenuator made from transite and coated with a high temperature
aluminum paint. The three lenses were double-convex with diam-
eters of 82 mm. and focal lengths of 89 mm. With these optics
the radiant flux was first focused at the near edge of the dust cloud and then on a miniature radiometer manufactured by RdF Stikon Corporation. When the radiometer was placed at the focus near the burner port, fluxes up to 65 cal./cm. sec. were obtained. Reduction of these fluxes by means of the attenuator was found to be well controlled and reproducible.

PROCEDURE

For burning velocity measurements, it was necessary to obtain a dust cloud of known properties (i.e., known dust concentration, oxygen percentage, flow rate, and temperature). The cloud was then ignited with a hand torch just above the heated stabilizer ring. Normally the resulting flame would anchor itself to the ring and remain there for periods ranging from about 1 second to 30 seconds, depending on the frequency and magnitude of fluctuations in the dust concentration. If the flame was found to be stable and free from serious fluctuations, a photograph of it was taken. Immediately thereafter, or immediately after making a temperature measurement, the stabilizer ring was swung out of position, causing the flame to be extinguished. A sample of the dust was then collected as promptly as possible for determination of its concentration.

The burning velocity relative to the cold cloud input was determined from the photographs by projecting the films and measuring the dimensions of a frustum of the flame inner cone. These dimensions were then corrected to scale and substituted in Dery's equation

\[ S_u = \left( \frac{2V}{\pi R^2} \right) \left\{ 1 - \frac{d_1^2 + d_2^2}{2R^2} \right\} \right) \left( 1 + \frac{(2h)}{(d_1 - d_2)} \right)^2 \]

where \( S_u \) is the burning velocity; \( V \) is the volume flow rate (at 25°C and 760 mm. Hg) of a cloud of radius \( R \); \( d_1 \) and \( d_2 \) are the diameters of the base and the top of the cone frustum; and \( h \) is the height of the frustum.

Although the visible cone frustum method is not the most accurate one for determining burning velocities, its absolute accuracy is probably within ±10 percent, while the precision attainable by using it for determining relative burning velocities is considerably better. It therefore is entirely adequate for the present work.

The burning velocity for methane-air flames was determined by a cone height method. In this method, the image is assumed to be a geometric cone of known radius; thus by measuring its height, the surface area of the cone can be calculated. The volume flow rate divided by the surface area of the cone gives the burning velocity.

The flame temperature measurement was made immediately after the photograph was taken, by moving the thermocouple probe horizontally into the region of the apex of the cone and feeding the e.m.f. produced directly to a pen recorder.

Dust concentration measurements were made by aspirating the entire cloud through a glass wool filter for a known time (usually 7 seconds). The weight of dust collected divided by the volume flow
of gas in the same time period yielded the dust concentration, on the assumption that the volume of dust was negligible relative to the gas volume. This assumption was accurate to within approximately 0.03 percent.

The procedure for the ignition studies consisted of generating a coal dust cloud of known concentration at a fixed oxygen percentage, and then impinging a small, known amount of radiant energy on the cloud for 20 or 30 seconds, after which the flux was increased until ignition occurred. In some instances the cloud was preheated to aid ignition.

**MATERIALS**

Virtually all gases used in this study were supplied in high pressure cylinders by the Matheson Company. Exceptions were the nitrogen for the burner jacket, supplied by the Linde Company, and the air used in the methane experiments, which came from a line in the building. Pertinent information on the gases used is given in Table I. All values are manufacturers' minimum standards.

The average particle sizes of the aluminum and graphite dusts were 9 microns and 5 microns respectively as given by the manufacturers. The mass median particle sizes of Coals I, II, and III were 6, 6, and 18 microns respectively as determined by the Particle Data Laboratories Inc. using a Coulter Counter technique. For the particle size distributions see Figure 5. The proximate analyses for these coals are given in Table II.
### TABLE I

**GASES USED IN INVESTIGATION**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Grade</th>
<th>Analysis</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>Extra Dry</td>
<td>99.6% O₂</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>Prepurified</td>
<td>99.996% N₂</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td>99% N₂</td>
<td>used in burner jacket</td>
</tr>
<tr>
<td>Air, dry</td>
<td></td>
<td>20.9% O₂</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>79.1% N₂</td>
<td>plus inert gases</td>
</tr>
<tr>
<td>Methane</td>
<td>C.P.</td>
<td>99.0% CH₄</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td></td>
<td>20.9% O₂</td>
<td>used in methane experiments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>79.1% N₂</td>
<td>plus inert gases</td>
</tr>
</tbody>
</table>

### TABLE II

**PROXIMATE ANALYSES OF COALS (AS RECEIVED)**

<table>
<thead>
<tr>
<th></th>
<th>H₂O%</th>
<th>V.M.%</th>
<th>ASH%</th>
<th>F.C. % (by diff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal I</td>
<td>1.6</td>
<td>34.2</td>
<td>5.5</td>
<td>58.7</td>
</tr>
<tr>
<td>Coal II</td>
<td>1.2</td>
<td>8.1</td>
<td>11.3</td>
<td>79.4</td>
</tr>
<tr>
<td>Coal III</td>
<td>2.0</td>
<td>35.2</td>
<td>8.1</td>
<td>54.7</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

The experimental results of the investigation are presented in this chapter with little comment. Critical comments are reserved for the following chapter—Discussion and Conclusions.

PARTICLE SIZE DISTRIBUTION FOR COAL DUSTS

Figure 5 shows the experimental results of the atmospheric oxygen content and burning velocity. A similar comment applies to the experimental relationship between burning velocity and flame temperature. The good correlation at large dust concentrations is thought to be significant, and a comparison of all the burning-velocity data for Coal I is

PARTICLE SIZE DISTRIBUTION FOR COAL DUSTS

Figure 5
The experimental results of the investigation are presented in this chapter with little comment. Critical comments are reserved for the following chapter, Discussion and Conclusions.

**Burning Velocity and Flame Temperature Data**

The burning velocity and flame temperature data are presented in Tables III, IV, and V. These data are expressed graphically in Figures 6, 7, 8, and 9. The positions of the curves in these figures were determined visually to minimize the deviation of each datum point. An exception to this procedure was made at the lean end where the most weight was given to the lower burning velocity values. The reason for this prejudice is given in the section entitled Errors and Precision.

Figure 9 shows the experimental relationship between the atmospheric oxygen content and burning velocity. There appears to be a rather simple correlation between the two when the dust concentration is fairly high (ca. 308 mg./l.), but no clear relationship can be discerned at the two other dust concentrations.

A similar comment applies to the experimental relationship between burning velocity and flame temperature. Since the good correlation at large dust concentrations is thought to be significant, and because it will be used in a theoretical analysis of the results, it is shown in Figure 10.

A comparison of all the burning velocity data for Coal I is
TABLE III

BURNING VELOCITIES AND FLAME TEMPERATURES FOR
COAL I AVERAGE OXYGEN, 24.1% 

<table>
<thead>
<tr>
<th>%O₂</th>
<th>Dust Concentration (mg/l)</th>
<th>$S_u$ (cm/sec)</th>
<th>$T_f$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.3</td>
<td>148</td>
<td>25.0</td>
<td>---</td>
</tr>
<tr>
<td>24.3</td>
<td>151</td>
<td>14.6</td>
<td>1612</td>
</tr>
<tr>
<td>23.0</td>
<td>191</td>
<td>25.8</td>
<td>1131</td>
</tr>
<tr>
<td>23.5</td>
<td>190</td>
<td>18.1</td>
<td>---</td>
</tr>
<tr>
<td>24.3</td>
<td>196</td>
<td>24.7</td>
<td>---</td>
</tr>
<tr>
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<td>248</td>
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<td>1169</td>
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<td>1088</td>
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<td>23.7</td>
<td>268</td>
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<td>1000</td>
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<td>24.3</td>
<td>276</td>
<td>18.4</td>
<td>1177</td>
</tr>
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<td>24.3</td>
<td>282</td>
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<td>---</td>
</tr>
<tr>
<td>23.7</td>
<td>307</td>
<td>22.0</td>
<td>1022</td>
</tr>
<tr>
<td>25.3</td>
<td>313</td>
<td>15.6</td>
<td>1056</td>
</tr>
<tr>
<td>%O₂</td>
<td>Dust Concentration (mg/l)</td>
<td>$S_u$ (cm/sec)</td>
<td>$T_f$ (°C)</td>
</tr>
<tr>
<td>-----</td>
<td>-------------------------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>27.1</td>
<td>167</td>
<td>---</td>
<td>1584</td>
</tr>
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<td>27.1</td>
<td>170</td>
<td>27.8</td>
<td>1517</td>
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<td>27.1</td>
<td>187</td>
<td>13.0</td>
<td>1570</td>
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<tr>
<td>28.5</td>
<td>216</td>
<td>20.7</td>
<td>1433</td>
</tr>
<tr>
<td>27.1</td>
<td>235</td>
<td>23.3</td>
<td>1530</td>
</tr>
<tr>
<td>28.4</td>
<td>270</td>
<td>28.0</td>
<td>1114</td>
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<td>28.4</td>
<td>298</td>
<td>23.8</td>
<td>1228</td>
</tr>
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<td>28.4</td>
<td>302</td>
<td>22.0</td>
<td>---</td>
</tr>
<tr>
<td>27.1</td>
<td>305</td>
<td>23.5</td>
<td>---</td>
</tr>
<tr>
<td>27.2</td>
<td>308</td>
<td>19.2</td>
<td>1210</td>
</tr>
<tr>
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<td>345</td>
<td>20.2</td>
<td>1321</td>
</tr>
<tr>
<td>27.2</td>
<td>(510)?</td>
<td>17.5</td>
<td>1099</td>
</tr>
<tr>
<td>%O₂</td>
<td>Dust Concentration (mg/l)</td>
<td>S_u (cm/sec)</td>
<td>T (°C)</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------</td>
<td>--------------</td>
<td>--------</td>
</tr>
<tr>
<td>30.0</td>
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<td>25.6</td>
<td>1247</td>
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<td>142</td>
<td>28.0</td>
<td></td>
</tr>
<tr>
<td>29.4</td>
<td>151</td>
<td>12.9</td>
<td></td>
</tr>
<tr>
<td>32.8</td>
<td>184</td>
<td>17.8</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>190</td>
<td>17.9</td>
<td>1678</td>
</tr>
<tr>
<td>30.0</td>
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<td>1583</td>
</tr>
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<td>31.1</td>
<td>198</td>
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<td>1434</td>
</tr>
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<td>30.0</td>
<td>234</td>
<td>21.7</td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>302</td>
<td>28.2</td>
<td></td>
</tr>
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<td>1562</td>
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<td>34.7</td>
<td>379</td>
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<td></td>
</tr>
<tr>
<td>34.7</td>
<td>403</td>
<td>20.6</td>
<td></td>
</tr>
</tbody>
</table>
Figure 6

BURNING VELOCITY VERSUS DUST CONCENTRATION OF COAL I FOR 24.1 PERCENT OXYGEN

Dust Concentration mg. per liter

Burning Velocity cm. per sec.
BURNING VELOCITY VERSUS DUST CONCENTRATION OF COAL I FOR 27.7 PERCENT OXYGEN

Figure 7
BURNING VELOCITY VERSUS DUST CONCENTRATION OF COAL I FOR 31.0 PERCENT OXYGEN

Figure 8
VARIATION OF BURNING VELOCITY WITH OXYGEN PERCENT

Figure 9
Figure 10

VARIATION OF BURNING VELOCITY WITH FLAME TEMPERATURE FOR AN AVERAGE DUST CONCENTRATION OF 308 mg/l.
COMPARISON OF BURNING VELOCITY VERSUS DUST CONCENTRATION OF COAL 1 FOR THREE OXYGEN PERCENTAGES

Figure 11
DUST CONCENTRATION OF COAL I AT MAXIMUM BURNING VELOCITY VERSUS OXYGEN PERCENT

Figure 12
presented in Figure 11. The change in dust concentration at the maximum burning velocity for Coal I in relation to different oxygen percentages is shown graphically in Figure 12.

A comparison of the stoichiometric dust concentrations for the whole coal and for the volatile matter, in relation to the three oxygen contents studied, is presented in Table VI. The calculations for the whole coal were made by using an ultimate analysis for a similar coal \(^{26}\). In the case of the volatile matter stoichiometry, the ultimate analysis was taken from Long's\(^7\) data for a similar coal.

The burning velocity and flame temperature data for blends of Coal I with Coal II are presented in Tables VII and VIII. These data are presented graphically in Figure 13. Figure 14 shows the variation in the maximum burning velocity for different blends of Coal I with Coal II.

### TABLE VI

**STOICHIOMETRIC DUST CONCENTRATIONS FOR WHOLE COAL AND VOLATILE MATTER**

<table>
<thead>
<tr>
<th>(%O_2)</th>
<th>Stoichiometric Concentrations (mg/l)</th>
<th>Dust Concentration at Maximum (S_u)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole Coal</td>
<td>Volatile Matter</td>
</tr>
<tr>
<td>24.1</td>
<td>119</td>
<td>344</td>
</tr>
<tr>
<td>27.7</td>
<td>137</td>
<td>396</td>
</tr>
<tr>
<td>31.0</td>
<td>153</td>
<td>445</td>
</tr>
</tbody>
</table>
### TABLE VII

**BURNING VELOCITIES AND FLAME TEMPERATURES FOR A BLEND OF 90.9% COAL I AND 9.1% COAL II**

<table>
<thead>
<tr>
<th>%O₂</th>
<th>Dust Concentration (mg/l)</th>
<th>S (cm/sec)</th>
<th>T_f (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.0</td>
<td>159</td>
<td>15.0</td>
<td>----</td>
</tr>
<tr>
<td>28.0</td>
<td>174</td>
<td>19.3</td>
<td>1199</td>
</tr>
<tr>
<td>25.3</td>
<td>221</td>
<td>22.3</td>
<td>1217</td>
</tr>
<tr>
<td>28.0</td>
<td>238</td>
<td>19.6</td>
<td>----</td>
</tr>
<tr>
<td>28.0</td>
<td>248</td>
<td>25.2</td>
<td>----</td>
</tr>
<tr>
<td>28.0</td>
<td>298</td>
<td>23.9</td>
<td>----</td>
</tr>
</tbody>
</table>

### TABLE VIII

**BURNING VELOCITIES AND FLAME TEMPERATURES FOR A BLEND OF 80% COAL I AND 20% COAL II**

<table>
<thead>
<tr>
<th>%O₂</th>
<th>Dust Concentration (mg/l)</th>
<th>S (cm/sec)</th>
<th>T_f (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.0</td>
<td>197</td>
<td>11.6</td>
<td>----</td>
</tr>
<tr>
<td>28.0</td>
<td>230</td>
<td>16.3</td>
<td>761</td>
</tr>
<tr>
<td>25.3</td>
<td>232</td>
<td>15.4</td>
<td>----</td>
</tr>
<tr>
<td>28.0</td>
<td>289</td>
<td>18.8</td>
<td>866</td>
</tr>
<tr>
<td>28.0</td>
<td>299</td>
<td>20.0</td>
<td>956</td>
</tr>
</tbody>
</table>
Attempts to study blends of 70% Coal I and 30% Coal II were unsuccessful. Stable flames could only be maintained for very short times (ca. 1/2 sec.), even at 35% oxygen. No burning velocity or flame temperature measurements could be performed in such brief intervals of time.

In a subsequent experiment to determine the effect of particle size, a burning velocity value of 19.5 cm./sec. was obtained for Coal III at 266 mg./l. and 28% oxygen. No other stable flames could be obtained at this oxygen content.

If coal dusts burn in a manner similar to that suggested by Long (cf. p. 7), then hydrocarbon flames with added, non-volatile dusts should show similar characteristics. To study this comparison, an experiment was designed to measure the burning velocities of methane-air flames with and without added dusts. A marked decrease in the burning velocity was observed when dust was added. In addition, the accompanying decreases in flame temperature, because of the heating of the dust particles and the increased radiation losses, were calculated. For similar decreases in burning velocity, these calculated values can be compared with the temperature decreases measured by Kaskan. The data and calculations for this experiment are summarized in Table IX.

**QUALITATIVE OBSERVATIONS**

In an exploratory work such as this, there are normally qualitative observations that warrant presentation. For instance, the coal dust flames studied in this work bore many similarities to
BURNING VELOCITY VERSUS DUST CONCENTRATION OF BLENDS OF COAL I WITH COAL II FOR 28 PERCENT OXYGEN

Figure 13
BURNING VELOCITY VERSUS PERCENT COAL II IN BLEND

Figure 14
TABLE IX
BURNING VELOCITIES FOR METHANE-AIR FLAMES WITH AND WITHOUT DUST ADDITION

<table>
<thead>
<tr>
<th>Type Dust Added</th>
<th>Dust Concentration (mg/l)</th>
<th>% Fuel (Methane)</th>
<th>$S_h$ (cm/sec)</th>
<th>$T^\circ C*$</th>
<th>$T^\circ C**$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>-----</td>
<td>11.4</td>
<td>25.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coal II</td>
<td>113</td>
<td>11.4</td>
<td>14.3</td>
<td>250</td>
<td>160</td>
</tr>
<tr>
<td>None</td>
<td>-----</td>
<td>11.4</td>
<td>24.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>170</td>
<td>11.4</td>
<td>6.4</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

* Calculated temperature decrease resulting from added dust (cf. Appendix)

** Reference 22

gaseous flames. They had flashback and blowoff limits and showed rather sharp inner cones (Figure 15).

One of the most striking features of these flames was their instability. Stable flames were very difficult to obtain and preserve. This might be explained by their extreme sensitivity to fluctuations in dust concentrations and to variations in the conditions at the stabilizer. The asymmetric cones and oscillations in the flame size which were frequently observed almost certainly were caused by the nonuniformity of the dust flow.

An experiment was devised to study the importance of volatile matter combustion on the control of the rate of flame propagation. Carbon tetrachloride, which is known to inhibit hydrocarbon
Typical Flame at 24.3% O₂ and 260 mg/l, $S_U=30$ cm/sec

Typical Flame at 26% O₂ and 268 mg/l, $S_U=33$ cm/sec

Flashback Flame

Blowoff Flame

PHOTOGRAPHS OF LAMINAR COAL DUST FLAMES

Figure 15
combustion, was introduced in increasing amounts upstream from the flame until the flame was extinguished. On three occasions when this was done, the flame front was seen to fade from view without a change in cone height, leaving only a cloud of glowing particles.

The radiant ignition experiments did not yield quantitative results since a systematic study was not made. However, they did show that the dust clouds ignited more readily with increases in preheat temperature, oxygen content and dust concentration. It was also observed, by motion pictures, that when ignition took place it usually began in a region 1 or 2 cm. above the location of the radiant beam.

**ERRORS AND PRECISION**

The true precision of the burning velocity data can not be estimated from known uncertainties in the variables in the Dery equation (i.e., volume flow rate and the frustum dimensions). Such an estimate would only give a minimum value for the error, which was about ± 6% in this work. The use of a visible Bunsen cone for burning velocity measurements has an inherent error of about ± 10%. In this work duplicate determinations of the burning velocity gave average deviations as high as ± 12%, which was considered to represent the lower limit of precision. The principal sources of this indeterminate error were the oscillations and asymmetric cones which were often observed in the flames.

It has been observed that disturbances in the flow created by a flame stabilizer do not affect measurements made downstream,
beyond the wake of the stabilizer. The use of the frustum method for burning velocity determinations avoids consideration of that part of the flame near the stabilizer, and therefore any perturbation introduced by such a device may be neglected.

The reproducibility of the method of measuring dust cloud concentration was checked several times. The average deviation was found to be ± 4%. Much larger deviations could possibly have been caused by agglomeration of the dust or by dust aggregates being scrubbed off the wall of the burner tube. This latter possibility is offered as an explanation for the anomalously high burning velocities observed for some low dust concentrations (cf. Figures 6, 7, and 8). The high values are probably spurious because: (1) fluctuations in dust concentration (as observed visually) were always upward surges rather than reductions; and (2) visual observation of decaying flames showed that when the dust concentration was reduced from values near the concentration at the maximum burning velocity, the burning velocity fell steadily.

The flame temperature measurements had two major sources of uncertainty; namely, the correction for radiation losses and the effect of possible catalytic activity at the thermocouple surface. Following Kaskah, the radiation correction was estimated to be from 40°C to 1000°C as the wire temperature changed from 1100°C to 1600°C. The effect of catalytic combustion remains enigmatic. In this work anomalously high temperature readings were obtained when the thermocouple was left in the flame for times as long as 5 seconds. Because of this uncertainty and the many
assumptions used to estimate the radiation correction, the flame temperature data are reported without corrections. It is thought that the absolute values reported are probably below the true values by margins of from 30°C to 100°C.

A check was made on the accuracy of the thermocouple measurements by comparing them with results obtained using an optical pyrometer. The current through a tungsten filament lamp was adjusted until the filament appeared similar in brilliance to a dust flame, as observed visually through a red filter. The brightness temperature of the tungsten filament was then measured with an optical pyrometer using a red filter. This temperature agreed with the temperature of the dust flame as measured by the thermocouple to within 20°C. While this agreement is interesting it can not necessarily be construed as valid support for the thermocouple measurement. The optical complexity of coal dust flames makes interpretation of these results extremely complicated.

The response time of the thermocouple-recorder system was also checked. It was found to be less than one second after the mullite insulation had been heated and only slightly above one second when the insulation was cold.
IV

DISCUSSION AND CONCLUSIONS

Examination of the burning velocity data shows agreement with the data of Long \(^7\) and Hattori \(^8\) if the different oxygen percentages are taken into account. From this observation, the self-consistency of the data, and the estimated uncertainty of the measurements, it can be concluded that the technique used is acceptable for observations of laminar dust flame behavior.

The principal observations made on the experimental data are listed below:

1. The burning velocity versus dust concentration curves have a definite parabolic shape.

2. The burning velocity maximum lies on the lean side of stoichiometric for the volatile matter, and on the rich side of stoichiometric for total coal (cf. Table VI).

3. The burning velocity maximum shifts to higher dust concentrations as the oxygen content is increased (cf. Figure 12).

4. The burning velocity curves widen as the oxygen content is increased.

5. On the rich side of the burning velocity maximum, both burning velocity and flame temperature increase in an approximately linear manner as the oxygen content is increased. (cf. Figures 9, 10 and 11).

6. Addition of anthracite decreases the burning velocity. This can be considered simply as a decrease in the volatile matter
content (cf. Figure 13).

7. Increasing the particle size of the dust decreases the burning velocity.

Several of these observations [(viz, 1), 3), and 4], are similar to observations made on gaseous flames\textsuperscript{29}, a fact which is consistent with the description of dust flames suggested by Long (cf. previous discussion). There are, however, marked differences between the dust flames studied here and normal gaseous flames. The most obvious distinction is the presence of dust particles in the flame, which should increase the importance of radiant heat transfer within the flame and to the surroundings. In addition, the production of coal dust flames requires that the gaseous fuel be supplied by devolatilization. This is more analogous to droplet combustion than to gaseous combustion.

The following qualitative model is considered to represent the combustion process in the bituminous coal dust flames in this work:

1. Preflame zone: Radiation and conduction heat up both particles and gas. Some volatile matter is released from the coal. Very little experimental information is available concerning the kinetics of devolatilization, so it is not possible to treat the evolution of volatiles quantitatively.

2. Preignition zone: Here conduction dominates the heat transfer. Expulsion of volatile matter is rapid; but the particle temperature rises less rapidly because the devolatilization is endothermic\textsuperscript{30}. At the end of the preignition zone the temperature
rises more rapidly as devolatilization slows down.

The volatiles expulsion tends to cause the particle temperature to lag behind the gas temperature. Radiation, however, tends to have the opposite effect. However, since heating of the gas by the particles is thought to be fast, it therefore is likely that dust and gas are nearly at the same temperature.

3. Ignition: Ignition is thought to occur when the gas temperature reaches about 600°C - 800°C. As with devolatilization kinetics, there is a dearth of information on ignition temperatures of dusts. Essenhig and Csaba express a preference for a low ignition temperature, around 375°C. Inflammator tests, of bituminous coal dusts in air yield temperatures in the neighborhood of 800°C. This result is probably too high, but by a margin that is exceedingly difficult to estimate.

Because of the small size of the particles, diffusional mixing of escaping volatiles with air will be quite fast. Therefore, ignition probably occurs in an essentially premixed gaseous system. At first thought, one might then suppose that the ignition temperatures should correspond to those observed, or estimated, for gaseous flames. However, the possible catalytic effect of particle surfaces complicates the ignition, so that a priori estimates of the ignition temperature are apt to be unreliable.

4. Gas combustion zone: The volatile matter is burned and the temperature rises rapidly to a value characteristic of the mixture. The remaining volatile matter is expelled and added to the flame in this zone. The temperature attained via combustion
of the volatiles will tend to rise as the dust concentration is increased toward the value for which a stoichiometric mixture of volatiles and oxygen-enriched air is achieved. This will be offset to a large extent by the increased radiation loss resulting from the higher particle concentration.

5. Residue combustion zone: The carbonaceous residue is consumed, in part or in toto, depending upon the dust concentration. The temperature drops sharply at the beginning of this zone because the slow combustion of the residues does not provide a heat release rate sufficient to compensate for radiation losses. This temperature behavior is substantiated by single-particle work, where the maximum radiation (maximum temperature) occurs during the rapid combustion of volatiles. Further support from the present work lies in the observation of a sharp radiation maximum in the flame front (cf. Figure 15, page 43).

The only theoretical approach to coal dust combustion that has been developed for quantitative predictions is Essenhigh and Csaba's modification of Nusselt's radiation theory (cf. page 5). However, this theory was designed for flames of large lateral extent and does not apply directly to small, laboratory-scale flames of the kind studied in the current work. Nevertheless, it appears that if a suitable geometric view factor is used to account for the small size; and if the lower optical density is considered, the values calculated from the theory are within a factor of five of the experimental data in the current work. A comparison of the experimental burning velocities with those predicted by the radiation theory (for dust
concentration of about 300 mg./l. is presented in Table X.

The data at dust concentrations around 300 mg./l. are used for comparisons between theory and experiment because it is in this concentration region that the simplest dependence of burning velocity upon flame temperature has been found experimentally (cf. Figure 10).

It is, however, improbable that in the flames under present study, radiation dominates in the heat transfer. Rough calculations indicate that for this flame system, both conduction and radiation were important. The relative contributions can be estimated by taking the conduction term as

\[ \lambda_i \left( \frac{\partial T}{\partial X} \right) \]

and the radiation term as

\[ \frac{(3w_d \rho_d r)}{(\rho_d d_f)} T_0 L_f \propto T_f^3 \left[ 1 - \exp \left( -\frac{3w_d L_0}{4\rho_d d_f} \right) \right] \]

neglecting the geometric view factor. A discussion of these terms is given on a later page.

Assuming

\[ \frac{(\partial T)}{(\partial X)} = \frac{(T_f - T_i)}{\delta f} \]

when \( T_f = 1600^\circ K \) (flame temperature at end of volatiles combustion zone)

\( T_i = 900^\circ K \). (This value is selected for the ignition temperature as a compromise between the two extremes cited previously. The use of either of the extreme values...
TABLE X

COMPARISON OF CALCULATED AND EXPERIMENTAL BURNING VELOCITIES AT DIFFERENT FLAME TEMPERATURES FOR DUST CONCENTRATIONS OF ABOUT 300 MG./L.

<table>
<thead>
<tr>
<th>$T_f$ ($^\circ$C)</th>
<th>$S_u$ (Calculated) (cm/sec)</th>
<th>$S_u$ (Experimental) (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1055</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>1210</td>
<td>6</td>
<td>19</td>
</tr>
<tr>
<td>1320</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>1560</td>
<td>12</td>
<td>31</td>
</tr>
</tbody>
</table>

(650°K or 1120°K) does not alter the conclusion based on the calculation.)

$\delta_r = 2$mm. (visually observed flame zone thickness)

$\lambda_i = 2 \times 10^{-4}$ cal./cm. sec. K. (This is the value for the thermal conductivity of nitrogen and it is considered typical for the gaseous mixture. The thermal conductivity of the solid particles may be neglected since they occupy less than 0.03 percent of the volume), the conduction term approximately equals 0.70 cal./cm.$^2$ sec.

And when $L_o = 6$ cm. (length of preheat zone)

$L_f = \text{flame thickness} = \delta_r = 2$ mm. (cf. subsequent discussion)

$w = 3 \times 10^{-4}$ g./c.c. (dust cloud concentration)

$\rho_d = 1.4$ g./c.c. (density of coal)

$r = 2.5 \times 10^{-4}$ cm. (particle radius)
\[ T_o = 298 \, ^\circ K \text{ (cold cloud temperature)} \]

\[ \sigma = 1.37 \times 10^{-12} \text{ cal./cm.}^2 \text{ sec. K}^4 \text{ (Stefan-Boltzmann Constant)} , \]

the radiation term approximately equals 0.21 cal./cm.\(^2\) sec.

These calculations show that both modes of heat transfer must be considered for a theoretical analysis of dust flames similar to those in the current work.

In setting up a propagation rate theory the guidelines will be taken from Cassel's heat balance equation. Dust and gas are assumed to have the same temperatures and linear velocities throughout.

The thermal flux through the ignition point for heating the cloud is equal to

\[ \phi_0 \rho_u \left[ C_p (T_i - T_o) + h_v \right] \]

where \( \phi_0 \) is the input density (dust plus gas), \( C_p \) is an average heat capacity for the cloud, \( T_i \) and \( T_o \) are the ignition and cold cloud temperatures respectively, and \( h_v \) is the latent heat for releasing that fraction of the volatile matter that is evolved in the preignition zone.

The thermal flux is comprised of an effective radiation flux and a conduction flux. The conduction flux is given by the product of the thermal conductivity of the mixture (\( \lambda_i \)) and the temperature gradient at the ignition point (\( \frac{\partial T}{\partial X} \)). It is then assumed that

\[ \frac{\partial T}{\partial X} \frac{r}{\delta r} \]
where $T_f$ is the flame temperature at the end of the volatiles combustion zone and $\delta_r$ is the thickness of the volatile matter combustion zone.

By a mass balance,

$$\delta_r = \frac{wV^2}{U}$$

where $w$ is the initial coal dust concentration, $V$ is the percent volatile matter, and $U$ is the average reaction rate in units of mass per unit volume in the volatile matter combustion zone.

The weak temperature dependence of the burning velocity indicates that the volatile matter combustion is not similar to a premixed gaseous flame and that the rate of decomposition of the coal is not controlling the kinetics in the gaseous combustion zone. Weak temperature dependence is possible if rate control rests either in the interdiffusion of volatile matter and oxygen or diffusion of the volatile matter out of the coal. Simple calculations show that the interdiffusion of the volatile matter and oxygen is probably too fast to be controlling. Consequently it seems that release of volatile matter from the coal is the rate-controlling factor. This conclusion is given further support by Burgoyne and Cohen, who found that for tetra lin droplets above 20 microns, the sprays burned as individual droplets. Below 10 microns the flame was blue with a coherent front. It is doubtful if coal particles of about 5 microns can release volatile matter as quickly as an evaporating drop of the same size. If they do release volatile matter very fast, then this evidence would predict essentially premixed behavior, which does
not seem to be true. This indicates that, although ignition occurs in a premixed system, rate control in the gaseous combustion zone probably lies in the rate of evolution of volatile matter out of the particles.

Devolatilization is an exceedingly complex phenomenon. At low temperatures, evolution of gaseous volatile matter is probably controlled by diffusion out of the pores of the coal. For bituminous coals, which normally have a low porosity, this would probably be Knudsen type diffusion. At higher temperatures, chemical decomposition of the coal, changing permeability of the coal matrix, and varying plasticity of the coal are possible complicating factors in an understanding of devolatilization.

The experimental results of the current work place an upper limit for the temperature dependency of the rate controlling process at about \( T_f^{2.5} \). A lower limit for this dependency is \( T_f^{0.5} \), which is the value normally used for Knudsen diffusion. A first-power temperature dependency has been observed experimentally for diffusion through carbon. In the absence of better information, a temperature dependency of \( T_f^{0.8} \) is chosen as a compromise.

Further support for diffusional control comes from the experiment with carbon tetrachloride. Additions of small amounts of carbon tetrachloride to the dust flame did not appear to affect the burning velocity but only extinguished the flame. Since there was no increase in cone height, signifying a decrease in burning velocity, attending the carbon tetrachloride addition, it must be concluded that the rate of the gas phase chemical reactions is not controlling
the thickness of the volatiles combustion zone. Changes in the thickness are reflected in a change of the thermal conduction flux to the unburned cloud. An alteration in this flux is expected to alter the burning velocity. Since interdiffusion almost certainly does not control the combustion rate of the volatiles, the only alternative possibility is that the release of volatile matter out of the coal particle in controlling the reaction rate. Devolatilization would not be affected by the inhibition of the gas phase chemical reactions. The observation that the burning velocity did not decrease when the chemical reactions were inhibited, but that the flame faded from view in an abrupt manner, is therefore compatible with rate control by devolatilization.

Thus, the average reaction rate may be expressed as

\[ U = k T_f^{0.8} \]

where \( k \) is a constant.

The radiation flux term is equal to the product of the absorptivity of the unburned cloud, the emissivity of the flame, a geometric view factor, the Stefan-Boltzmann constant, and the fourth power of the absolute temperature.

The absorptivity of the unburned cloud is given by

\[ 1 - \exp \left(-3wL_0/4\rho_d r^2\right) \]

where \( w \) is the concentration of dust particles of density \( \rho_d \) and radius \( r \), and \( L_0 \) is the length of the preheat zone in the cold cloud. This term is the same as the radiation attenuation term used by Essenhigh and Csaba (cf. page 5). This implies that the
absorptivity will always be approximately unity.

The emissivity of the flame is given approximately by

\[
\frac{(3 \pi L_f^2)}{(4 \pi d^2)} \left( \frac{T_0}{T_f} \right)
\]

where \( L_f \) is the flame thickness. This term is similar to the one used by Cassel (cf. page 6) except that in the present work the expansion of the dust cloud in the flame zone is considered. This expression assumes that \( (1 - e^{-x}) = x \), which is a good approximation for \( x \leq 0.2 \).

The flame temperature used here is an average value for the volatile matter combustion zone. Because thermal conduction in the gas is probably rapid\(^3\), the temperature gradient between the gas in the vicinity of a particle and the gas mid-way between particles can be neglected. The temperature rise in the flame front, in the direction of flow, is also thought to be fast and thus most of the cloud in the volatiles combustion zone may be considered to be at some high temperature which is near the maximum temperature reached when the volatiles have been burned. Therefore, in the absence of better information, \( T_f \) is set equal to the maximum temperature, which should be close to the experimental flame temperatures as measured with the thermocouple.

Attempts to elucidate the nature of the geometric view factor for small flames were unsuccessful. Because of the lack of knowledge on this subject, the geometric view factor is represented by \( F \).

The radiation flux is then given by
\[ F \left( \frac{3w L_f T_d}{4 \rho_d r T_f} \right) \sigma T_f^4 \left[ 1 - \exp \left( -\frac{3w L_o}{4 \rho_d r} \right) \right] \]

where \( \sigma \) is the Stefan-Boltzmann constant.

On further study of this radiation term, it appears that \( L_f \) can be approximated by setting it equal to \( \delta_r \). From thermocouple measurements, the temperature is known to fall off quite rapidly beyond the flame front. A sharp decrease in radiation above the flame front was also observed visually and photographically (viz. Figure 14). A similar observation was made by Essenhigh\(^{12}\) for single particle combustion, where he found an intensity during volatile combustion roughly five times the average during residue combustion. This was for a coal having a volatile matter content similar to Coal I. The combination of temperature and geometry should cause the volatiles flame to be the dominant region for radiant transfer to the unburned cloud. Apparently the reaction rate is fast in the flame front but much slower beyond it in the residue combustion zone. There the radiation losses exceed the heat release rate and the flame is extinguished.

The resultant heat balance equation can be written as

\[
S_u \phi_o [C_p (T_i - T_o) + h_v] = \frac{\lambda i (T_f - T_i) k T_f^{0.8}}{S_u (w)} \\
+ \frac{(w)(V)}{k T^{0.8}} \left( \frac{3w T_o}{4 \rho_d r} \right) F \sigma T_f^3 \left[ 1 - \exp \left( -\frac{3w L_o}{4 \rho_d r} \right) \right] 
\]

Simplifying, by taking \( E = \phi_o [C_p (T_i - T_o) + h_v] \)

\[
\alpha = (w)(V)
\]
\[ C = \lambda (T_f - T_i) \]
\[ K = k T^{0.8} \]
\[ R = \frac{(3wT_0)}{(k^2 \rho d^2)} F \sigma T_f^3 \left[ 1 - \exp \left( -\frac{3wL_0}{4 \phi d} \right) \right] \]

and substituting in the above equation gives

\[ S_u E = \frac{C K}{\alpha S_u} + \frac{\alpha S_u R}{K} \]

Rearranging, the expression for \( S_u \) becomes

\[ S_u^2 = \frac{C K}{\alpha E} \frac{1}{1 - \frac{\alpha R}{KE}} \]

This is essentially the form of the equation derived by Cassel et al., but including the modifications previously mentioned.

On the basis of this theoretical treatment of flame propagation in coal dust clouds, burning velocity behavior can be predicted thus:

1. Decrease in particle size increases the burning velocity.

2. Increase in the average flame temperature (caused by increase in oxygen content or by increase in flame size, thus decreasing radiation losses) increases the burning velocity.

3. Decrease in the ignition temperature (such as has been observed by increasing the oxygen content) increases the burning velocity.

4. The effect of dust cloud concentration \((w)\) on the
burning velocity is confused by the dependency of several of the terms in the equation on \( w (\varphi, C_p, T_i, 37 \text{ and } T_f \text{ all depend on } w) \). Examination of the expression does yield some information however. There is a low \( w \) below which no flame can exist (i.e., \( T_f < T_i \)). On increasing \( W \), \( T_f \) increases, and \( S_u \) goes up. There must also be a critical value for \( w \) where \( T_f \) levels off because of large radiation losses to surroundings. Beyond this point \( S_u \) decreases as \( w \) increases.

One obvious shortcoming of this analysis is that it sheds no light on the nature of the geometric view factor. All that can be said is that \( F \) approaches unity for large flames; and for small flames is less than unity by an amount that is extremely difficult to estimate on the basis of present knowledge.

In spite of the approximate nature of the treatment, the qualitative predictions based on it are consistent with the experimental findings. It also appears that estimations of the burning velocity calculated from this treatment are almost within the precision of the experimental data.

Taking \( h_v = 0 \) (This term is thought to be very small but there is no quantitative information on it that would apply to the present study)

\[ F = 1 \] Because of the lack of information on this factor it is chosen as unity. It is probably lower, but by an amount that can not be estimated on the basis of present knowledge.

\( \xi_r = 0.2 \text{ cm.} \) (This is an average value for all
the flame fronts as measured with a ruler. Since the thickness of the flame front only varied by about 15 percent this value is used for all the calculations.

\[ T_i = 900^\circ K \] (This value is chosen as being more probable than the extreme values mentioned previously. Calculations are also presented for these ignition temperatures \(650^\circ K.\) and \(1120^\circ K.\)) to point up the limitations of the theoretical analysis.)

\[ T_0 = 300^\circ K. \]

and assuming the other terms to be the same as those given in the previous calculation, then for a 300 mg./l. dust cloud the calculated burning velocities are those given in Table XI along with comparative experimental values.

**TABLE XI**

**COMPARISON OF BURNING VELOCITIES, CALCULATED BY RADIATION-CONDUCTION EQUATION AND EXPERIMENTAL VALUES AT VARIOUS TEMPERATURES**

<table>
<thead>
<tr>
<th>( T_f )</th>
<th>( S_u ) (Calculated)</th>
<th>( S_u ) (Experimental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^\circ C )</td>
<td>( T_i = 650^\circ K. )</td>
<td>( 900^\circ K. )</td>
</tr>
<tr>
<td>----------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>1055</td>
<td>28</td>
<td>12</td>
</tr>
<tr>
<td>1210</td>
<td>35</td>
<td>16</td>
</tr>
<tr>
<td>1320</td>
<td>41</td>
<td>19</td>
</tr>
<tr>
<td>1560</td>
<td>53</td>
<td>27</td>
</tr>
</tbody>
</table>
While these calculated values are only approximate, the close comparison with experimental results for the 900°K ignition temperature augurs well for future work on the theoretical approaches to an understanding of coal dust flames.

It is possible to obtain further information on the heat balance equation by an analysis of its temperature dependency. For

\[ S_u^2 = \frac{CK}{\alpha E} \left( \frac{1 - \alpha R}{KE} \right) \]

the temperature dependence is as follows:

- \( C \) varies with \( (T_f - T_i) \)
- \( K \) varies with \( T_f^{-0.8} \)
- \( R \) varies with \( T_f^3 \)
- \( E \) and \( \alpha \) are considered independent of temperature.

Thus, if all terms, other than temperatures, are held constant, the equation takes the form

\[ S_u = A \sqrt{T_f - T_i} \frac{T_f^{0.4}}{\sqrt{1 - BT^2}} \]

where \( A \) and \( B \) are constants.

By substituting the experimental burning velocities and flame temperatures (cf. Table XI) in the above equation, simultaneous solution of two sets of data yields a value for \( B \). For burning velocity comparisons at flame temperatures below about 1300°C, an ignition temperature of 800°C requires that \( B \) have a zero value; whereas for ignition temperatures in the range of 400°C to
700°C., B has a finite value. This variation in B serves to point up the importance of the ignition temperature in the heat balance equation.

The value of B, determined for $T_i = 400^\circ$C. and for $T_f$ from 1056°C. to 1560°C., is $0.15 \times 10^{-6}$. This value for B gives $\frac{\alpha R}{KE} = 0.29$ at 1956°C., and 0.57 at 1560°C. The term $\frac{\alpha R}{KE}$ may be considered to be the ratio of the radiation to the chemical kinetics; and therefore the marked increase in its value over this temperature interval is what would be expected.

The dependency of the equation upon particle size can be analyzed in a manner similar to that used for the temperature dependence study. For

$$S_u^2 = \frac{CK}{\alpha \frac{R}{KE}}$$

the particle size dependence is as follows:

- $E$, $\alpha$ and $C$ are independent of particle size
- $R$ varies with $\frac{1}{r}$
- $K$ varies with some inverse power of $r$, (viz., $n$).

Thus, if all terms other than particle size are held constant, the equation takes the form

$$J \sqrt{r^{-n}}$$

For Coal III (average particle size about 20 microns) a burning velocity of 20 cm./sec. was determined for 266 mg./l. For Coal I (average particle size about 5 microns) the burning
velocity was about 30 cm./sec. for 266 mg./l. It should be noted that, for this comparison, the particle size values are merely convenient parameters representing the particle size distribution. The validity of this analysis thus lies in the similarity of the particle size distribution curves. A cursory comparison of the curves for Coal I and Coal III shows that they are indeed similar in shape.

If $K$ varies with $\frac{1}{r}$, it is readily seen that the data do not fit the equation. If, however, $K$ varies with $\frac{1}{r^2}$ or $\frac{1}{r^3}$, the data do fit the equation. This indicates that the reaction rate varies with the reciprocal of either the particle area or the particle volume, but which is more important is not known.

The theoretical treatment that has been presented offers no obvious explanation for the location of the burning velocity maximum between stoichiometric for total coal and stoichiometric for the volatile matter. However, there appear to be two possibilities which, combined, could help to elucidate the problem:

1. As the dust concentration increases, the radiation losses also increase, thus lowering the flame temperature and the burning velocity.

2. Some of the fuel particles are combusted in the volatiles combustion zone, thus shifting the maximum burning velocity away from stoichiometric for the volatile matter toward stoichiometric for the whole coal. This would apply especially to the very small particles (<1 micron) which could be completely burned in the
reaction zone. 38

A second problem has not been dealt with in the treatment outlined here, namely the absence of a simple correlation between burning velocity and flame temperature for dust concentrations below about 280 mg./l. The answer to this problem presumably lies somewhere in the complex interrelationship between radiation losses, dust concentrations, and oxygen contents. Future work may reveal the details of this relationship. The present analysis has relied upon the empirical fact that the relationship is simplest when the dust concentration is largest. Within this limitation, the results of the analysis are encouraging and seem to support the treatment used.

According to the theoretical treatment developed here for small laminar coal dust flames, the combustion of volatile matter plays a crucial role by providing a region of sharp temperature increase which promotes both conductive and radiative heat transfer. When anthracite was added to bituminous coal dust suspensions, the proportion of available volatile matter diminished and therefore the heat transfer decreased, thus decreasing the burning velocity (cf. Figure 13, page 40).

While this fact is important to an understanding of anthracite combustion, it should not impair the utility of anthracite in practical pulverized fuel systems. The reasons for this are:

1. In large systems, and particularly in systems with hot furnace walls, radiation losses to surroundings are relatively unimportant.
2. In most practical systems there is aerodynamic recirculation which effectively increases the input temperature. The result of recirculation is to increase the burning velocity and decrease the importance of thermal conduction across the flame front.

Confirmation of these comments is provided by the work of Beer and Thring, who studied the burnout of residues from pulverized anthracite combustion in a furnace of 18 inches diameter with walls at 900°C or more. Simulated recirculation (by injection of hot gases in the preignition zone) was found to increase the rate of flame propagation by a factor larger than three.

The theoretical study of Essenhigh and Csaba provides further support for these comments. Their analysis indicates that rapid flame propagation is still possible in a system where volatile content is low or absent, by a purely radiative mechanism, provided that the flame is sufficiently large. The present work permits a lower limit of about one inch diameter to be set for such a flame when there is no recirculation. The evidence for this lies in the ability to ignite but not to stabilize suspensions of anthracite, with oxygen contents up to 50 percent, using the 2 cm. burner. Cassel has stabilized flat flames of graphite dust in pure oxygen on burners of about 1 cm. diameter, and has demonstrated that the burning velocity rises as flame diameter increases.

Thus the main conclusion concerning anthracite combustion in practical furnaces, from this work, is that no barrier to its use is evident. The effect of volatile content should be unimportant, except as it may effect decrepitation of particles. Flame propagation
will depend on the particle size, the oxygen content, and the recirculation, through the effects that these variables have on the propagation-controlling radiant heat transfer.

Using a visible flame cone extinction method, burning velocities were determined for a high volatile coal dust in mixtures containing 14.6, 27.7, and 41.9 percent oxygen. The measurements gave good agreement with the results of other researchers although there were some for the different oxygen contents. The maximum value for the burning velocity occurred between stoichiometric for the whole coal and stoichiometric for the volatile matter. This phenomenon may be caused by (1) the increased radiation losses accompanying the raising dust concentration which causes the flame temperature (and, therefore, the burning velocity) to decrease; and (2) the contribution of some of the residue particles in the volatile matter combustion zone.

Blends of anthracite with bituminous coal were also studied. The burning velocity of flames of these blends was observed to increase as the relative amount of anthracite was increased. This may be interpreted simply as a decrease in the volatile matter component.

On the basis of experimental observations and analysis of the weak temperature dependence of the burning velocity, it is suggested that reaction control in the flame front lies in the release of
SUMMARY AND SUGGESTIONS

This work has had as its main objective the determination of the conditions for establishing laminar coal dust flames and the measurement of the burning velocity of these flames.

Using a visible flame cone frustum method, burning velocities were determined for a high volatile coal dust in mixtures containing 24.0, 27.7, and 31.0 percent oxygen. The measurements gave good agreement with the results of other research if allowances were made for the different oxygen contents. The maximum value for the burning velocity occurred between stoichiometric for the whole coal and stoichiometric for the volatile matter. This phenomenon may be caused by (1) the increased radiation losses accompanying the rising dust concentration which causes the flame temperature (and, therefore, the burning velocity) to decrease; and (2) the combustion of some of the residue particles in the volatile matter combustion zone.

Blends of anthracite with bituminous coals were also studied. The burning velocity of flames of these blends was observed to decrease as the relative amount of anthracite was increased. This may be interpreted simply as a decrease in the volatile matter content.

On the basis of experimental observations and analysis of the weak temperature dependence of the burning velocity, it is suggested that reaction control in the flame front lies in the release of
volatile matter from the coal.

A theoretical treatment of small laminar coal dust flames pointed up the importance of conductive as well as radiative heat transfer. On the basis of a heat balance equation that included both conduction and radiation, qualitative predictions that agreed with the experimental findings were made concerning the effects of the variables on the burning velocity.

There are several lines of research suggested by the current work. Measurements of the radiant flux and the temperature profile of the flame front would certainly be very useful. For making such measurements, a flat flame might prove more satisfactory than a Bunsen flame. It also seems desirable to make further studies of the dust addition to gaseous flames and the chemical inhibition of the gas phase reactions.

Another experiment that warrants consideration is a study of the effect of flame size. Information from such work would have a direct bearing on the nature of a geometric view factor.

It also seems evident that studies on the devolatilization of coal, for conditions similar to those in a flame, would be essential to increased understanding of coal dust flames.
REFERENCES


In order to calculate the radiation losses, a cylindrical model was chosen to represent the flame cone. The walls of the cylinder were not equal to the flame cone thickness, and its height and diameter equal to the cone height and the diameter of the flame base respectively. Using this model, the radiation flux was then calculated from

$$ K = \frac{2}{\pi} \frac{\tau}{T} $$

where $K$ is the radiation loss, $\tau$ is the time of a mole of methane to reach the flame, $\tau$ is the Stefan-Boltzmann constant, $\tau$ is the emissivity of the flame front, $A$ is the area of the model cylinder, and $T$ is the flame temperature.

<table>
<thead>
<tr>
<th></th>
<th>Particle Size (microns)</th>
<th>Dust Concentration (ppm)</th>
<th>Flame Radiant Heat Loss (kcal/hr)</th>
<th>Heat per Mole of Methane (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>9</td>
<td>113</td>
<td>6.5</td>
<td>4.76</td>
</tr>
<tr>
<td>Anthracite</td>
<td>9</td>
<td>113</td>
<td>6.5</td>
<td>4.15</td>
</tr>
</tbody>
</table>
CALCULATION OF FLAME TEMPERATURE LOWERING OF A METHANE-AIR FLAME BY DUST ADDITION

The calculation of the temperature decrease attending dust addition to a methane-air flame requires the determination of a balance between the heat generated by the combustion reaction and the sum of the heat carried off by the gaseous products, the heat carried off by the particles, and the radiation losses caused by the dust. The temperature at which this balance is obtained can then be subtracted from the adiabatic flame temperature to yield the temperature decrease.

In order to calculate the radiation losses, a cylindrical model was chosen to represent the flame cone. The walls of the cylinder were set equal to the flame zone thickness; and its height and diameter equaled the cone height and the diameter at the flame base respectively. Using this model, the radiation flux was then calculated from

\[ R = t \sigma \varepsilon_c A T_f^4 \]

where \( R \) is the radiation loss, \( t \) is the time for 1 mole of methane to reach the flame, \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon \) is the emissivity of the flame front, \( A \) is the area of the model cylinder, and \( T_f \) is the flame temperature.

<table>
<thead>
<tr>
<th>Dust</th>
<th>Particle Size (microns)</th>
<th>Dust Concentration (mg/l)</th>
<th>Flame Radiant Heat Loss per Mole of Methane Burned (kcal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>9</td>
<td>170</td>
<td>8.5 ( T_f = 1800^\circ K ) 3.65 ( T_f = 2000^\circ K ) 5.56</td>
</tr>
<tr>
<td>Anthracite</td>
<td>6</td>
<td>113</td>
<td>3.8 8.16 12.4</td>
</tr>
</tbody>
</table>
The heat carried off because of the heat capacity of the product gases and the dust was calculated to be

<table>
<thead>
<tr>
<th>Gaseous Products</th>
<th>$T_f=1800^\circ\text{K}$</th>
<th>$T_f=2000^\circ\text{K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>116.3</td>
<td>133.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>15.5</td>
<td>17.3</td>
</tr>
<tr>
<td>Anthracite</td>
<td>9.3</td>
<td>10.6</td>
</tr>
<tr>
<td>Graphite</td>
<td>13.9</td>
<td>16.3</td>
</tr>
</tbody>
</table>

The heat of reaction per mole for a methane-air flame containing 11.4 percent fuel is calculated to be 157.2 kcal. It is then readily seen that a heat balance is obtained for the aluminum and anthracite dust at about $2000^\circ\text{K}$. For the graphite dust the heat balance is obtained at $1950^\circ\text{K}$. by interpolating between $1800^\circ\text{K}$ and $2000^\circ\text{K}$. The adiabatic flame temperature for the pure methane-air flame has been calculated to be $2250^\circ\text{K}$. This gives the following temperature decreases:

<table>
<thead>
<tr>
<th>$\Delta T^\circ\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Anthracite</td>
</tr>
<tr>
<td>Graphite</td>
</tr>
</tbody>
</table>

(Note: The adiabatic flame temperature calculated here is approximately 4 percent higher than similar calculations reported elsewhere. Since several approximations were made in the present calculation, it is probably in error by about the 4 percent stated.)