IGNITION AND COMBUSTION OF ISOLATED COAL WATER SLURRY DROPLET

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ABSTRACT
A digital image processing technique is used to investigate the ignition and combustion characteristics of an isolated coal water slurry droplet in low Re flow. Coal water slurry droplet study is useful for dilute coal suspensions based on the premise that ignitability of a spray of coal water slurry must depend on the ignition characteristic of an isolated coal water slurry droplet. A flat flame burner is used for optical accessibility and also for simulating vitiated gases as existing in boiler burners. A quartz wire of 0.175 mm dia is chosen for low thermal conductivity to hold the droplet above the flat flame burner. The following sequence of events are observed: (i) Ignition occurs at the leading edge of the droplet, (ii) For coal water slurry droplet of the order less than 1 mm ejection of volatiles as jets in the direction of convective flow followed by coalescence, (iii) For a droplet with diameter of the order greater than 1 mm it was observed that the volatile combustion occurs away from the droplet in the wake of the combustible gases made upstream, (iv) Combustion of coal water slurry droplet is intermittent. Ignition time and volatile combustion times were obtained for a typical coal water slurry droplet. Calculations were carried out to determine the number of particles, interparticle spacing and density of coal water slurry droplet.

NOMENCLATURE
CWS - coal water slurry
PT - RH - platinum - rhodium
f - focal length
ms - milliseconds

* corresponding author

Ti - ignition temperature
T_{peak} - highest temperature reached.
T_{e} - temperature of coal water slurry droplet
m_{l} - mass of liquid
m_{s} - mass of solid
t_{v} - time taken for volatile combustion
t_{e} - evaporating time
t_{h} - heating time
t_{i} - ignition time

INTRODUCTION AND LITERATURE REVIEW
Coal liquid mixtures (CLM) have been considered as boiler fuels in the past but never with the urgency that existed in the late 1970s when oil prices rose dramatically and security of supply was a primary concern to the industrialized nations. Thambimuthu and Whaley [11] believe that CLM such as coal water mixtures (CWM) offer the potential to partially or completely replace oil or natural gas as a boiler fuel in retrofit situations, as well as being an alternative coal-based liquid fuel for new boiler designs. Furthermore low capital cost of conversion of existing boilers, site-specific considerations, such as space limitations or restricted access through residential areas, favor liquid fuel transportation and handling. Its easy transportability, low T_{peak} value are factors in its favor. Most CLM manufacturing processes also include a coal benification stage which removes ash and sulfur, thereby reducing emissions of these products. Low NO_{x} and CO emission make it an attractive fuel too. Also at present gasification and liquefaction of coal, although fundamentally attractive, are prohibitively expensive. All these factors have

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fueled many investigators to conduct fundamental experiments in this area.

Most studies have been concentrated on the ignition and combustion of isolated coal particles. This study of the ignition and combustion of coal-water slurry droplet may be useful for dilute coal suspensions, based on the premise that ignitability of a spray of coal-water slurry must depend on ignition characteristic of an isolated coal-water slurry droplet. Also it may be useful to adopt droplet combustion as a model problem to gain insight on the mechanisms governing complex heterogeneous combustion systems.

The objective of the current study is to use a digital image processing technique to investigate the ignition and combustion characteristics of an isolated coal-water slurry droplet. A flat flame burner is selected because of optical accessibility and also for simulating the vitiated gases as existing in boiler burners.

The literature on ignition and combustion of coal-water slurry droplet is very limited and fundamental mechanisms have only recently become understood according to Law [13]. Law [13] believes that the widely different physical and chemical properties of constituents of these hybrid fuels necessitates consideration of multicomponent effects in an essential way.

Lee and Law [9] have shown that the droplet gasification in a hot oxidizing environment of freely falling carbon slurry droplet as consisting of two periods: An initial period of regressing droplet size governed by the classical d^-2 law, and subsequently d^-3 law period during which (a) the droplet size remains fixed by a rigid porous shell, (b) gasification takes place through the shell with a constant rate, (c) the diameter of the inner surface of the shell regresses, with a rate which varies cubically with time, and (d) an internal, expanding vapor cavity is formed whose diameter also varies cubically with time. Furthermore only the liquid component participated in gasification, as is reasonable to expect. Miyasaka and Law [10], Turner and Faeth [8], Liu and Law [2] and Turner et al [3] have shown that when particle agglomeration occurs during slurry droplet combustion the total droplet lifetime consists of a relatively short initial period, during which liquid vaporization and particle agglomeration occur, followed by a very long period of agglomerate burning. Thus research on slurry droplet combustion has emphasized two aspects, namely the initial gasification process leading to agglomerate formation [2,8,10] and the subsequent burning of the agglomerate.

Fu et al [6] have given a method for estimating the heating time (t_h), evaporating time (t_e), ignition time (t_i) and ignition temperature (T_i) for a single coal-water slurry droplet. Charlesworth and Marshall, Jr. [4] have advanced a theory for predicting the formation of a solid phase in drying a droplet containing a dissolved solid; by means of a sensitive balance Charlesworth and Marshall, Jr. [4] were able to find weight changes with time during evaporation and observe the time of appearance of the first solid phase and the formation of a solid crust for a wide range of drying conditions and materials.

Elperin and Krasovitov [12] used a quasi-steady approxim ation in analyzing the evaporation of slurry droplets. They used two models (1) droplet with crust and (2) droplet with bubble. Both models consider the evaporation and drying of slurry droplets to occur in two stages. During the first stage immediately after injection of the slurry droplet into the ambient hot air, the droplet is assumed to be composed mainly of liquid and its evaporation rate is assumed to be controlled by the gas phase resistance. During evaporation the amount of liquid mass m_l decreases while the solid mass m_s remains constant and the droplet diameter continuously shrinks. At some critical solid liquid mass ratio the discrete solid particles form an agglomerate while the voids between particles are still filled with liquid. At this moment, which is assumed to occur at the pre-specified critical solid-liquid mass ratio, the second stage of drying begins. This ratio of m_s/m_l was found to be 5.35 for lime-water slurries according to Abuaf and Staub [1]. Elperin and Krasovitov [12] model takes into account the effects of compressibility and filtration of a gas-vapor mixture within the porous shell. They have shown that in the case of small temperature differences in the neighborhood of a slurry droplet at the second stage of drying, the regime of slow evaporation and saturation occurs and in the case of high temperature differences the pressure of the gas-vapor mixture within the porous shell significantly increases leading to the fragmentation of a porous shell.

Pourkashanian et al [9] studied droplet combustion phenomenon for coal oil mixtures using a combination of gravimetric, thermometric and chemical analytical technique and concluded that the most important parameters that govern the suitability of the colloidal coal is (i) the initial rate of evolution of volatile components, which determines the ignition and the initial combustion characteristics, and (ii) the rate of char burnout, which controls the overall burning time.

None of these studies however have photographic observable data of the ignition process. There is no data on the t_i vs. diameter of CWS and t_e vs. diameter of CWS. In this study we propose to use a digital image processing technique to investigate the same.

**EXPERIMENTAL SET UP**

The experimental facility which will be used for the current study centers around three components: flat flame burner, particle suspension system and digital image processing system.

**Flat Flame Burner and Particle Suspension System**

The burner consists of a water cooled 6.6 cm, sintered porous disk surrounded by a porous shroud ring for the introduction of a shielding gas (nitrogen) flow to suppress aerodynamic instabilities (Figure 1). The burner is of cylindrical construction. Water is used as the active cooling medium to facilitate rapid flame stabilization. A mixture of methane and air is used as a flammable mixture to establish the flat flame. Two flow meters 0 to 5 SCFH and 0 to 100 SCFH are used for methane and air flows respectively. The O_2 concentration can be controlled either by injecting N_2 or by regulating air flow at some fuel flow rate. Additional flowmeter is used for nitrogen. Fine quartz wires, between 0.170 -0.180 mm. in
diameter and 150 mm. long, are utilized to hold coal water slurry (CWS) droplet samples at the sharpened tip of the wire. The quartz wires themselves are held in position with the aid of clamp and stand. The quartz support system is selected since CWS droplet are expected to release volatile in jets which result in the propulsion of particle away from the field of focus. Further the inter-particle spacing can not be controlled. Consequently in order to reduce the interference from quartz rod, larger sized particles are used.

A flash arrestor is provided so that the flame may not propagate back to the cylinder. And finally a ceramic plate is provided to shield the drop from the gases initially. This again is held in position with the aid of clamp and stand. Methane and air are premixed in the mixing chamber and the premixed gases passed through a flash arrestor device into the burners. The flash arrestor prevents any flame from propagating back to the fuel.

CWS droplet is suddenly exposed to the hot (fuel used is CH₄) vitiated environment provided by the flat flame burner by withdrawing the ceramic plate. The images of the combustion process are captured through the digital image processing system and analyzed. The CID2250D digital camera is adjusted to take images of the flame and set up. A CWS droplet is then taken at the tip of the quartz wire and fixed to a clamp at the other end with the droplet hanging down right above the flame, the flame being covered by the ceramic plate. The plate is now removed and the camera activated through the framegrabber. The images are stored in the buffer of the computer. The images are sequentially analyzed to observe the processes taking place during evaporation and combustion. The images can be manipulated (the number of images can be increased by decreasing the area of focus of the camera) and also specific areas of the image can be analyzed by zooming to that particular area of the image for more details. The most important governing parameters in the evaporation/decomposition of the CWS droplet are the gas temperature and the oxygen concentration in the vitiated gases generated by the flat flame burner. A 0.02 inch PT-RH thermocouple is used to measure gas temperature at different heights, ranging between 10 mm to 50 mm from the surface of the flat flame burner. The oxygen concentration is controlled by controlling the air flow. The coal used to make the coal water slurry was obtained from the DOE, Pittsburgh and the proximate and ultimate analysis of the coal is given in Table 1. The composition of the chosen CWS drop was 60-40 % by weight of coal and water respectively. Flocon was added as a stabilizer in the ratio of 5 gm of itself to 1000 gm of coal.

Digital Image Processing System

The system consists of a CID2250D digital camera (f = 25 mm, 512x512 pixels) with each pixel scanned over 100 Ns, an image processing board which digitize up to 20 million samples per second, an image processing software which operates the frame grabber to perform image acquisition, display, and processing and a high resolution color video Sony monitor (900Hx200 V pixels). The high resolution color monitor (Sony PVM-1342Q) is integrated with the image processing system to provide a tool for visual observation of both the digitizing and display processes.

PROCEDURE FOR THE EXPERIMENT

First the flat flame burner is lit, and the flame is allowed to stabilize on the top of the sintered disk forming a flat flame. The
RESULTS AND DISCUSSION
The size of the CWS drop used were 0.8 mm, 0.9 mm, 1.1 mm and 2 mm respectively. The diameter of particles of coal used were between 32 and 45 mm. The results for a typical droplet size of .9 mm are shown in Table 2.

DENSITY OF MIXTURE

| Density Coal | 1300 kg/m^3 |
| Density water | 1000 kg/m^3 |
| Dia of droplet | 0.9 mm |
| # of Particles | 6843,504663 |
| Dia of Part | 58.5 micrometer |
| Mass fraction | Coal 0.6, Water 0.4 |
| Density CWS | 1160,714286 Kg/m^3 |

The calculations were carried out to determine the number of particles, interparticle spacing and density of CWS. The following assumptions were made.
(a) CWS is made up of coal and water, (b) The weight of flocon is negligible, (c) Coal particle of diameter 38.5 mm on the average was chosen for calculation purpose (d) The density of water chosen was 1000 kg/m^3 and density of bituminous coal was 1300 Kg/m^3.

As mentioned earlier the temperature profile was measured with the aid of a Pt-Rh 0.002º thermocouple and they are shown in Fig. 2 for methane flow rate of 1.5 SCFH and air flow rate of 32 SCFH which corresponds to 12.2% O2 concentration. The temperature at the horizontal plane at 40 mm is shown by the unbroken line. For the experiment the CWS droplet was kept at the center of the flat flame burner at a height of 40 mm where the temp was about 1495K. Temperature profiles at heights of 10, 20, 30, 50 mm above the flat flame burner were also obtained.

The typical droplet combustion being discussed here was magnified by a factor of 15 and observed at a height of 50 mm from the burner surface where the temperature was about 1471K.

Observations - Once the cover plate is withdrawn the flame took 120 ms (4 frames) to reach the drop. It took the flame 390 ms (13 frames) to heat up, vaporize the water and also to heat up the coal [ignition time]. It took another 390 ms (13 frames) for the CWS to pyrolyse. Volatile combustion time was of the order of 240 ms (8 frames). And the whole experiment was over in 1020 ms. In the 13 frames taken for ignition, streaks were observed across the monitor. At the 18th frame we can see the flame develop above the CWS droplet. This phenomenon interpreted as initial flaming [Annanmalai [7]] where premixed volatile and air mixture accumulated and ignites consuming all the volatiles in the gas phase. However coal particle temperature is not high enough to maintain the pyrolysis. The glow observed is due to heterogeneous ignition of particles at the leading edge which raises the temperature of the particle at the leading edge. The flame then disappears and develops again at the 22nd frame. At the 23rd frame, a black region is observed at the center of the flame which seems to move away at the 25th frame. The reason is that the region is void of O2, seems to be like a black region containing fuel rich mixture while the oxygen diffuses and maintains the flame around the black region. At the 26th frame only the residue is left glowing indicating that the volatiles are burnt.

The flame lift off distance was calculated to be about 0.48 mm and the flame height 1.174 mm. Droplet of diameter 1.5 mm and 0.8 mm was subsequently used without any magnification. When a CWS droplet of size 1.5 mm was placed above the flame it took the flame about 5 frames to reach the quartz rod (about 150 milliseconds) (Fig. 4).

In the frame by frame shot of the combustion process we can see that the combustion just above the CWS droplet and then we can see the flame being carried away from the CWS and combustion occurs at a distance. The reason could be because of bulk gas flow the volatiles are carried away from the CWS droplet and also the fact that volatile are being ignited as they are released and move away from the CWS droplet. The volatile liberation rate and the bulk flow control the wake and by increasing the bulk flow to a limit can lead to blow off. In the subsequent frame a single char particle seems to have been formed. The original number of particles seem to break up. This probably occurs at the weakest bond. And
again combustion occurs but now it seems to be 2 particle combustion.

When a CWS droplet of size 0.8 mm was placed above the flame it took the flame about 4 frames to reach the quartz wire (about 120 milliseconds). Figure 5 gives the details of the combustion process.

A couple of other experiments were conducted at height 40 mm where the temperature is about 1495 K. The results are presented below. For a 0.94, 1.5, 1.91 and 2.79 mm CWS drop the ignition time and volatile combustion time were about 210 ms and 360 ms; 210 ms and 660 ms; 720 ms and 1320 ms and 990 ms and 2220 ms respectively.

[frame # 18]

[frame # 19]
Sequence of CWS droplet combustion (magnified images)

FIG 3

CWS droplet combustion of diameter of order greater than 1 mm.

FIG 4

CWS droplet combustion of diameter of order less than 1 mm

FIG 5
Table 3 gives the details of the combustion process. Figure 6 and Fig. 7 gives the observed relation between initial droplet size and ignition time and volatile combustion time. The $R^2$ observed assuming a linear model between diameter and ignition time was 0.90 and that observed between diameter and volatile combustion time 0.97.
Analysis of the Combustion Steps

<table>
<thead>
<tr>
<th>Frame</th>
<th>Time (ms)</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0</td>
<td>Plate removed at this point</td>
</tr>
<tr>
<td>17</td>
<td>390</td>
<td>Glow observed in the monitor</td>
</tr>
<tr>
<td>18</td>
<td>420</td>
<td>Initial flaming observed</td>
</tr>
<tr>
<td>22</td>
<td>540</td>
<td>No sustained ignition</td>
</tr>
<tr>
<td>23</td>
<td>570</td>
<td>Sustained ignition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>commences</td>
</tr>
<tr>
<td>26</td>
<td>660</td>
<td>Volatile combustion complete</td>
</tr>
<tr>
<td>ti - 390</td>
<td>tcv - 660</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3**

ACKNOWLEDGEMENTS

The partial support of the Energy Resources Program of the State of Texas is greatly acknowledged. Currently experiments are in progress to monitor Ti vs. Time.

REFERENCES


