2006

The measurement of flame propagation within an electrostatic particulate system

Ryan Mark Kroll
Iowa State University

Follow this and additional works at: http://lib.dr.iastate.edu/rtd
Part of the Mechanical Engineering Commons

Recommended Citation
The measurement of flame propagation within an electrostatic particulate system

by

Ryan Mark Kroll

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Mechanical Engineering

Program of Study Committee:
Gerald M. Colver, Major Professor
Fred L. Haan, Jr.
Kenneth M. Bryden

Iowa State University
Ames, Iowa

2006

Copyright © Ryan Mark Kroll, 2006. All rights reserved.
# Table of Contents

List of Figures ........................................................................................................ iv
Nomenclature ......................................................................................................... vi
Acknowledgments ................................................................................................ xi
Abstract .................................................................................................................. xii

Chapter I: Background .......................................................................................... 1
  Introduction ......................................................................................................... 1
  Electrostatic Particulate Suspensions ............................................................... 2
  Present Study .................................................................................................... 3

Chapter II: Literature Review ............................................................................... 4
  Electrostatic Suspension of Particles ............................................................... 4
  Combustion of Gasses ................................................................................. 14
  Combustion and Quenching in Particulate Clouds .................................... 17

Chapter III: Experimental design and calibration ............................................. 24
  Overall Experimental Design and Setup ....................................................... 24
  EPS Chamber Design .................................................................................. 25
  EPS Circuit Design and Data Acquisition .................................................. 26
  Gas Flow Calibration ................................................................................. 36
  Particle Number Density Calibration ......................................................... 41
  Particle Preparation .................................................................................... 42

Chapter IV: Results .............................................................................................. 48
Test Setup ................................................................................................................. 48
Results and Discussion .............................................................................................. 51
Chapter V: Summary, Conclusions and Recommendations ................... 71
  Summary .................................................................................................................. 71
  Conclusions .......................................................................................................... 72
  Recommendations ................................................................................................. 73
Appendix A: Propane in Circular Rig ................................................................. 75
Appendix B: Natural Gas in Linear Rig ............................................................... 78
Appendix C: Natural Gas in Linear Rig ............................................................... 83
Appendix D: Natural Gas and Copper Particles .............................................. 85
Appendix E: Natural Gas and Diffused Copper Particles ............................ 86
Appendix F: Natural Gas and Diffused Aluminum Particles ..................... 87
Appendix G: Error Analysis ............................................................................... 88
Bibliography ........................................................................................................... 96
List of Figures

**Number**  **Page**

1. Particle in an electrostatic field ................................................................. 5
2. Particle number density with respect to height in an EPS .......................... 13
3. Burning velocity vs. particle concentration of aluminum ....................... 22
4. Aluminum aerosol flame ................................................................................. 23
5. Initial circular EPS chamber lower electrode ........................................ 28
6. Initial circular EPS chamber ........................................................................ 28
7. Final circular EPS chamber upper electrode ........................................... 29
8. Final circular EPS chamber lower electrode ............................................ 30
9. Final circular EPS chamber upper electrode ............................................ 31
10. Final EPS chamber lower electrode ....................................................... 32
11. Circular EPS chamber setup ....................................................................... 33
12. Linear EPS chamber upper electrode ...................................................... 34
13. Linear EPS chamber setup ........................................................................ 35
14. Second EPS chamber circuit ....................................................................... 37
15. Third EPS chamber circuit .......................................................................... 37
16. Final EPS chamber circuit .......................................................................... 38
17. Linear EPS chamber circuit ........................................................................ 39
18. EPS DAQ system .......................................................................................... 40
19. Rotameter setup ........................................................................................... 44
20. Rotameter calibration curve ............................................. 45
21. Particle number density curves from Lambert-Beer law ........ 46
22. Copper spheres, 53-63 microns ......................................... 47
23. Aluminum particles, 30-35 micron ..................................... 47
24. Circular rig propane-air combustion and spark .................... 49
25. Circular rig lean aluminum in air suspension and spark ......... 50
26. Circular rig DAQ output file showing voltage spikes .......... 52
27. Circular rig propane-air burning velocity data .................. 53
28. Circular rig natural gas test ............................................. 57
29. Linear chamber test of 4.6% propane in air ...................... 58
30. Linear chamber test of 5.8% propane in air ...................... 58
31. Linear chamber test of 6.9% propane in air ...................... 59
32. Linear chamber test of 8.0% propane in air ...................... 59
33. Linear chamber combustion test .................................... 60
34. Linear chamber combustion test .................................... 61
35. Linear chamber combustion test .................................... 62
36. Burning velocity ratio of propane and air ....................... 63
37. Burning velocity ratio of natural gas and air ................... 64
38. Burning velocity of copper and natural gas in air ............. 69
39. Burning velocity of aluminum and natural gas in air .......... 70
Nomenclature

\begin{align*}
A & \quad \text{Area} \ [\text{m}^2] \\
B & \quad \text{Mass Distribution} \ [\text{kg/m}^3] \\
\mathit{c}_p & \quad \text{Specific heat at constant pressure} \ [\text{J/kg K}] \\
D & \quad \text{Mass diffusivity} \ [\text{m}^2/\text{s}] \\
d & \quad \text{Diameter} \ [\text{m}] \\
e & \quad \text{Coefficient of restitution of a particle collision} \\
E & \quad \text{Electric field strength} \ [\text{kV/m}] \\
F & \quad \text{Force} \ [\text{N}] \\
g & \quad \text{Gravitational acceleration} \ [\text{m/s}^2] \\
h & \quad \text{Height above lower electrode} \ [\text{m}] \\
l_0 & \quad \text{Laser intensity with no particulate suspension} \ [\text{mW}] \\
l_s & \quad \text{Laser intensity during particulate suspension} \ [\text{mW}] \\
J & \quad \text{Current flux} \ [\text{A/m}^2]
\end{align*}
\( K \) Constant of Equation (16)

\( k \) Thermal Conductivity [W/m K]

\( l \) Distance [m]

\( m \) Particle mass [kg]

\( N \) Particle number density [particles/m\(^3\)]

\( n \) Quantity

\( p \) Pressure [\( \text{Nm}^2 \)]

\( Q \) Charge on a particle [C]

\( q \) Charge on a particle [C]

\( \dot{q} \) Heat flux [W/m\(^2\)]

\( r \) Radius of a particle [\( \text{m} \)]

\( r_f \) Reaction rate [kmol/m\(^3\) s]

\( RR \) Rate of reaction [is]

\( T \) Temperature [K]

\( t \) Time [s]
\( V \)  Applied voltage [V]

\( V_0 \)  Bed feed velocity [m/s]

\( W \)  Total Mass [kg]

\( \chi \)  Mole fraction

\( x \)  Position [m]

Greek

\( \alpha \)  Thermal diffusivity [m\(^2\)/s]

\( \delta \)  Thickness of the reaction zone [m]

\( \gamma \)  Extinction Coefficient

\( \varepsilon \)  Permittivity [F/m]

\( \mu \)  Viscosity [kg/m s]

\( \rho \)  Density [kg/m\(^3\)]

\( \phi \)  Stoichiometric mole fraction

Subscripts

\( an \)  Annulus
b  Bottom

c  Cross-sectional

cyl  Cylinder

D  Drag

E  Electrostatic

f  Fuel

fl  Float

I  Image

ig  Ignition

L  Laminar

L  Loss

l  Laser path

L.L.  Lower limiting

L.O.  Lift Off

P  Particle
\[ p \]  Product

\[ R \]  Reaction

\[ r \]  Reactant

\[ s \]  Separation

\[ T \]  Turbulent

\[ t \]  Top

\[ tr \]  Transmitted

Other Symbols

\[ \bar{\text{Average}} \]

\[ [] \]  Concentration

\[ \cdot \]  Derivative [1/s]
Acknowledgments

The author wishes to express sincere appreciation to NASA for supplying the funding for this and past projects under grant #NCC3846. Thanks to Dr. Colver for all his help throughout the research and writing process. Also, thanks to Dr. Haan and Dr. Bryden for their assistance in the preparation of this manuscript. In addition, special thanks to Mr. Hua Xu, Dr. Woods, Dr. Weber, and Mr. Jim Deutramont whose expertise and efforts contributed to successful completion of this study. Thanks also to the members of the school council for their valuable input and my family and my wife, Rachel, who was willing to follow anywhere I needed to go.
Abstract

A variant of the Electrostatic Particulate Chamber was developed to directly measure flame propagation velocity of combustible gas and powder mixtures. Flame propagation velocity was measured by tracking the position of the flame front utilizing the ionization effect and current due to a high intensity applied electric field. The position of the front was determined with respect to time by monitoring the voltage spike and current flow through spatially separated resistors.

With this technique, the flame propagation velocity was initially tested in gas mixtures of propane/air and natural gas/air. Measured velocities were compared to published values for burning velocities of laminar premixed flames. Although the data trends compared well to expected behaviors, the values measured were higher than expected, likely due to turbulent effects.

Additionally, burning measurements were taken in propane/air mixtures with various concentrations of 53-63\(\mu\)m copper particles acting to quench the flame. At low copper concentrations the burning velocity was increased. However, as copper particle concentration was increased the measured burning velocity quickly dropped below the burning velocity of similar mixtures without copper particles.

The propagation velocity of 30-35\(\mu\)m aluminum particles in a natural gas/air mixture was also measured. The measured velocity was found to be higher than the measured propagation velocity of the natural gas/air mixture without the
aluminum particles. The brightness of the flame also indicated ignition of the aluminum particles.
Chapter 1

Background

1.1 Introduction

Combustion is one of the oldest energy sources utilized by man. Even as technology has progressed through the ages, our dependence on combustion has changed, but has not lessened. As recently as 1989, 89% of the energy produced in the U.S. came from combustion sources [1]. In addition to energy production, combustion is essential for industrial processes such as refining of metals, production of cement, and waste disposal.

Despite the wide-ranging and important applications of combustion, much is unknown regarding quenching effects and burning of powders. This lack of knowledge is due to the complex nature of combustion systems, which utilize aspects of thermodynamics, heat and mass transfer, fluid dynamics, and chemistry, and which must be examined utilizing empirical and analytical methods. Many problems in combustion have been solved only in idealized forms, with real-life situations differing significantly from the idealized solutions.

According to Goroshin et al [2] the primary restriction on the advancement in understanding dust combustion is the lack of fundamental data. The ISU-NASA
research team has been working to expand that knowledge base with respect to 1-g and low-g powder combustion. In the last several decades, microgravity combustion has grown in significance. The combustion process of microgravity combustion differs significantly when the buoyant effects associated with gravity are removed as demonstrated by the spherical shape of a candle flame in microgravity. In addition, the combustion behavior of metal powders is of special significance due to the high energy content and ability to oxidize with carbon dioxide. Therefore, the ISU-NASA research team was formed with the goal of increasing the knowledge of powder combustion. In addition, the ISU-NASA research team set a goal of developing a standardized method of testing the behavior of powder combustion in 1-g and micro-g environments. These goals led to further development of the Electrostatic Particulate Suspension (EPS) and Electrostatic Particulate Suspension Test (EPST).

1.2 Electrostatic Particulate Suspensions

The EPS method utilizes essentially a parallel plate capacitor with two plate electrodes, separated by an insulating chamber that can be filled with gases and/or powder materials. An electric field is produced when a voltage difference is applied between the electrodes. When particles are placed in the chamber they behave as small capacitors, charging to the same potential and sign as the electrode they contact. When the electrostatic force on the particle is large enough, it will lift off the bottom plate and oscillate between the two plates, with the sign of the charge on the particles oscillating according to the electrode last
contacted. When many particles are placed between the electrodes, a particle cloud will be produced and motion will be further complicated with particle-particle interactions. This particle cloud will remain in dynamic equilibrium as long as the electric field remains unchanged.

1.3 Present Study

The EPS provides a unique opportunity to examine flame front (burning) velocities. Burning velocity is the most common method for characterizing premixed laminar flames [3]. Burning velocity is limited at the low end by gravity induced buoyancy effects and at the high end by the onset of compressibility. Within this range the burning velocity is determined by the flame thickness, reaction rates and times, composition of mixture, temperatures of flame and surroundings, molecular transport properties, flame shape, as well as pressure of the system [2,3].

The focus of the present study is to further expand the fundamental knowledge base in the combustion field by developing a variation of the EPS chamber to measure burning velocities directly. The new EPS chamber has been used to measure flame propagation velocities in gas mixtures as well as gas mixtures with inert particles. In addition, the effect of varying the electric field on the flame propagation velocities has been tested and will be examined.
Chapter 2

Literature Review

2.1 Electrostatic Suspension of Particles

Colver [1976] conducted an experiment in which he investigated the dynamic charging of dielectric and metallic particles in contact with a conducting plate in the presence of an applied DC electric field. Particles as small as 29 μm were electrically charged while in dynamic or stationary contact with either wall of a charged parallel plate capacitor. The charging process is a result of the capacitance effect of the particles in which the particle takes on a charge of the same sign and magnitude as the contacting wall. He determined that for both dynamic and stationary charging the formula \(^1\)

\[ Q = 4\pi \varepsilon r^2 E K \]  \hspace{1cm} (1)

applies, where \( Q \) is the equilibrium charge on the particle, \( E \) is the applied electric field strength, \( \varepsilon \) is the permittivity, and \( r \) is the radius of the particle.

\(^1\) In Colver [1976] the Maxwell charge distribution formula given in equation [1] is used; however, in many later papers a formula (such as equation [7]) is replaced with the equivalent Maxwell charge

\[ Q = \left(\frac{r^3}{6}\right) d^2 E \]

where \( d \) is particle diameter.
Figure 1: A particle in an electrostatic field, $Q$ is the charge on the particle, $r$ is the particle radius, $E$ is the applied electric field strength, $g$ is the acceleration due to gravity, $x$ is the separation distance from the infinite conduction wall, $F_E$ is the electrostatic force, $F_g$ is the gravitational force, and $\phi = 0$ is taken as zero ground potential.
He determined $K$ was equal to 1.64 for both dynamic and stationary charging of metallic particles and less than 1.64 for dielectric particles. Colver also determined this charging process tended to drive the particles away from the plates due to the electrostatic force which can be expressed as

$$F_j = QE$$  \hspace{1cm} (2)$$

where $Q$ is the charge on the particle and $E$ is the electrostatic field. An image force opposes the electrostatic force and can be expressed as

$$F_i = \frac{Q^2}{(4\pi\varepsilon)x_s^2}$$  \hspace{1cm} (3)$$

where $Q$ again is the charge on the particle, $\varepsilon$ is the permittivity, and $x_s$ is the effective separation distance of the charges on the particle and its image.

If the charge on the particle is great enough the particle will be driven by the electrostatic forces into cyclic motion. Image forces and body forces such as gravity, viscous drag, and inelastic collisions with the wall limit the maximum particle velocity. This cyclic motion will continue as long as the electrostatic field remains. The motion of a single particle due to the influence of an electrostatic field, ignoring fluid drag, can be described by the equation
\[
\frac{d^2 x_p}{dt^2} = \frac{QE}{m} \pm g
\] (4)

where \(x_p\) is the position of the particle, \(m\) is the mass of the particle, and \(g\) is the acceleration due to gravity. From the above equation of motion Colver [1976] derived the average velocity of a single particle to be

\[
\overline{S}_p = (1 + e) \left( \frac{l}{8} \right)^{\frac{1}{2}} \left( \frac{1}{1 - e^2} \left( \frac{QE}{m} \right) + \frac{g}{1 + e^2} \right)^{\frac{1}{2}} \left[ \frac{1}{1 - e^2} \left( \frac{QE}{m} - \frac{g}{1 + e^2} \right) \right]^{\frac{1}{2}}
\] (5)

where \(l\) is the distance the particle travels, and \(e\) is the coefficient of restitution. Colver also derived the lower limiting velocity to be

\[
S_{LL} = \left[ \frac{(1 + e)^2 L g}{4(1 + e^2)} \right]^{\frac{1}{2}}
\] (6)

Experimental values for the coefficient of restitution \(e\) were found to agree well with the value 0.68. The electric field strength required for sustained particle motion is given to be

\[
E_{LL} = \left[ \frac{(1 - e^2)}{(1 + e^2)} \frac{mg + F_D}{\frac{6}{\pi^3} \epsilon_0 d^2} \right]^{\frac{1}{2}}
\] (7)

Colver [1983] added the second term \((F_D)\) to account for viscous drag which can be approximated...
\[ F_D = 3\pi\mu S_p \left[ 1 + \frac{3d\rho S_p}{16\mu} \right]^{\frac{1}{2}} \]  

(8)

where \(d\), \(\mu\), and \(\rho\) are the particle diameter, fluid viscosity, and fluid density respectively, and the particle Reynolds number is given to be

\[ \text{Re}_p = \frac{\rho S_p d}{\mu} \]  

(9)

and is less than 100.

It should also be noted that the electrostatic force on the particle at the lower limiting electric field for sustained particle motion is less than the force required to lift a single conducting sphere from plane in a uniform electric field

\[ F_{L.O.} = \pi \varepsilon_0 D^2 E^2(1.37) \]  

(10)

as given by Lebedev and Skal’skaya [1962].

Colver [1980] described particle motion within the particle cloud of an open EPS system. In an open EPS system particles are driven away from a lower electrode but do not rebound off of the upper electrode. The equation of motion for a single particle is
where $\tau$ is the inertia-viscous drag relaxation time and $S_P$ is the particle velocity.

Colver also used the equations of conservation of mass, current flux and Gauss’s law in one dimension

\[ \dot{m} = mNS_p \]  \hspace{1cm} (12)

\[ J = QNS_p \]  \hspace{1cm} (13)

\[ \frac{dE}{dx} = \frac{QN}{\varepsilon_o} \]  \hspace{1cm} (14)

to derive the velocity of the particles to be

\[ S_p = \left( \frac{QF_s \tau}{m} \right) \left[ 1 - \frac{J}{\varepsilon_o E_s} - \frac{mg}{QF_s} \left( 1 - e^{-\frac{t}{\tau}} \right) \right] + \left( \frac{QJ}{m\varepsilon_o} \right) t + S_0 e^{\frac{-t}{\tau}} \]  \hspace{1cm} (15)

where $S_0$ is the bed feed velocity of the system.

Within a particle cloud system the charging and discharging of the particles on contact with either electrode will result in a vertical current flux

\[ J = KNQS_p \]  \hspace{1cm} (16)
For an idealized uniform particle density system with non-interacting particle $K=1$, however, in any real system $K<1$. Colver and Cotroneo [1978] developed an expanded form of the above equation which included collision phenomena

$$J = fNQS_F e^{-\alpha} + \gamma \left(1 - e^{-\alpha}\right)$$  \hspace{1cm} (17)$$

The first term in the brackets is to account for the particles in the system that move a distance $l$ without a collision, the second term accounts for the remaining particles. The terms $f$, $\sigma$, and $\alpha$ are included to account for particle history effects due to randomizations from collisions, irregular bounces, and particle rotation.

Colver and Cotroneo [1978] also expanded on the equation of average velocity of a particle given in equation (5) to include terms for the coefficient of restitution of the particle collision with both the upper ($e_t$) and lower ($e_b$) electrodes.

$$\overline{S_p} = \left(\frac{l}{8(1-e_t^2e_b^2)}\right)^{1/2} \left[\frac{1}{1-e^2_t \left(\frac{qE}{m}\right) + \left(1-e^2_t\right)g} \right]^{1/2} \frac{1}{(1+e_b)} + \left[\frac{1}{1-e^2_b \left(\frac{qE}{m}\right) - \left(1-e^2_b\right)g} \right]^{1/2} \frac{1}{(1+e_t)}$$  \hspace{1cm} (18)$$

In situations where particles accumulate on the lower electrode $e_b$ may significantly differ from $e_t$.

In addition to vertical motion the diffusion of particles has been studied. Colver and Howell [1978] electrostatically suspended 74-81$\mu$m and 125-147$\mu$m copper
particles in a horizontal rectangular duct. The particle number densities were then measured by three independent methods: (1) electrical current, (2) laser beam attenuation, and (3) count or weight measurement. It was shown that the diffusion process is significant apart from fluid dynamic driving forces. It was observed that the diffusion of particles within an electric suspension satisfies Fick’s Law. It was also observed that the self-diffusion coefficient is on the order of $10^{-3}$ m$^2$/s and increases with increasing electric field strength or decreasing particle diameter. Colver and Howell [1980] attributed the diffusion within the electrostatic suspension to one or more of the following processes: (1) gradients in the electric field strength along the duct due to special variations in net charge concentration, (2) random motion due to particle-particle collisions and particle-wall collisions.

Particle collisions, in addition to randomizing motion, reduce the effective charge on the particles. This along with charge shielding would result in a particle gradient effect, or stratification [Colver, 1983].

Shoshin and Dreizin [2002] examined this stratification effect and derived an equation for the electric field strength between the plates to be

$$\begin{align*}
E &= \frac{4 V_0}{3 \eta} \left( \frac{h}{h_i} \right)^{1/3}.
\end{align*}$$

(19)
where $V_0$ is the capacitor voltage, $h_t$ is the top electrode height, and particle-electrode and particle-particle interactions are neglected. The distribution of particle mass concentration then becomes

$$B = mN = \frac{16 \varepsilon \varepsilon_0 V_0^2}{27 gh_t} \left(\frac{h}{h_t}\right)^{\frac{1}{3}}$$  \hspace{1cm} (20)

where $m$ is the mass of a single particle and $N$ is the particle number density.

Greene [2004] also experimentally examined particle stratification effects in suspensions of copper and glass particles as well as glass bubbles. Near the lower electrode the data collected were similar in shape to the form predicted by Shoshin and Dreizin [2002], but a scaling factor was required. Near the upper electrode particle number density did not match the above equation, but instead was found to increase in a similar manner to the lower electrode. Greene attributed this to particle-electrode collision effects. It was also found the stratification effects, shown in Figure 2, were more pronounced with copper particles and negligible using glass bubbles, due to the low mass to surface area ratio.

Colver and Ehlinger [1988] experimentally verified the velocity of particles within an electrostatic suspension by leaking particles out of the top of an EPS chamber.
The particles were then captured on epoxy coated slides at various heights. By comparing the number of particles that stuck to the slides at the various heights a velocity distribution was determined. Colver and Ehlinger [1988] determined that the velocity can be described with a Maxwellian distribution

\[
\frac{dN}{dS} = \left[ \frac{4N}{S_o \sqrt{\pi}} \left( \frac{S}{S_o} \right)^2 \right] \exp \left[ -\left( \frac{S}{S_o} \right)^2 \right]
\]  

(21)

where \(dN/dS\) is the number density of particles in the speed range \(S\) to \(S+dS\).
Figure 2: Particle number density within an EPS chamber with respect to height demonstrating stratification effects.
For copper particles, the most probable speed \((S_0)\), was found to be 68, 76, and 60 cm/s for 44-53, 63-75, and 105-125 \(\mu\)m particles respectively in electric field strengths of about 12 kV/cm. A study by Eimers [2002] also expanded on this work.

### 2.2 Combustion of Gases

To determine the steady-state burning velocity a variety of methods have been employed. These methods are generally divided into three categories: thermal theories, diffusion theories, and comprehensive theories. The earliest and most well known thermal theory was put forth by Mallard and Le Chatelier in 1883 [16, 17]. They divided the flame into two zones, a preheat zone and an ignition zone. Within the preheat zone the gases are heated to the ignition temperature by conduction from the reaction zone. In the ignition zone the temperature continues to rise to the final post-combustion temperature as chemical enthalpy is converted into sensible enthalpy.

The energy balance within the preheat zone can be described as

\[
\dot{m}_p c_p (T_{ig} - T_r) = \frac{k}{\delta_r} (T_p - T_{ig}) \tag{22}
\]

where \(T_{ig}\) is the ignition temperature, \(T_r\) is the temperature of the reactants, \(T_p\) is the temperature of the products, \(k\) is the thermal conductivity, \(c_p\) is the specific heat, and \(\delta_r\) is the thickness of the reaction zone.
By realizing that the burning velocity is defined as the mass flow rate \((\dot{m})\) divided by the gas density the above equation can be rearranged to determine the laminar burning velocity to be

\[
V_L = \frac{\alpha}{\delta} \frac{(T_p - T_{ig})}{(T_{ig} - T_r)}
\]  

(23)

where \(V_L\) is the laminar burning velocity, \(\alpha\) is the thermal diffusivity, \(\delta\) is the flame reaction thickness, \(T_p\) is the temperature of the products, \(T_{ig}\) is the ignition temperature of the mixture, and \(T_r\) is the temperature of the initial reactants.

Mallard and Le Chatelier also determined that the laminar burning velocity can be described as

\[
V_L = \left[ \frac{\alpha}{\delta} \frac{(T_p - T_{ig})}{(T_{ig} - T_r)} RR \right]^{\frac{1}{2}}
\]  

(24)

where \(RR\) is the reaction rate. Although Mallard and Le Chatelier never specified \(RR\) it can be determined from chemical kinetics that

\[
RR = \frac{\bar{r}_f}{[n_f]}
\]  

(25)

based on initial fuel concentrations \(([n_f])\) and the global reaction rate \(\bar{r}_f\) as the change in fuel concentration with respect to time. It has been observed both
experimentally and theoretically that the reaction rate takes on the exponential form of an Arrhenius relationship

\[
\overline{r_f} = -AT^n p^m \exp\left(\frac{-E}{RT}\right)[n_f][n_{O_2}]
\]

(26)

where \([n_f]\) is the fuel concentration, \([n_{O_2}]\) is the oxidizer concentration. The constants \(A\) and \(E\) are often experimentally derived and are the global reaction rate constant and the activation energy respectively. For many cases, \(n\) and \(m\) can be set equal to zero for specified temperature and pressure ranges.

In diffusion theories the effects of the thermal energy transfer to the unburned gas is insignificant compared to the effects of the diffusion of active radicals. Tanford and Pease [16] compared hydrogen concentration in CO-O_2-N_2 flames versus flame velocity and found

\[
\overline{V_L} = \sqrt{\frac{C_r}{X_p} \sum \frac{k_i p_i D_{i,0}}{B'_i}}
\]

(27)

where \(C_r\) is the concentration of the reactant mixture, \(X_p\) is the mole fraction of the products, and \(B'_i\) is a function of the mass diffusivity of the gases in the reaction zone, the kinetic parameter, and the laminar flame speed.

By considering only the H and OH radicals in moist carbon monoxide flames and adding a 17 cm/s constant, Tanford and Pease determined
Calculated values generally had errors of less than 25%.

The comprehensive theories of Zel’dovich, Frank-Kamenetsky, and Semenov have expanded on the theory of Mallard and Le Chatelier to include diffusion and species conservation [16]. They determined

\[ S_L = 17 \frac{cm}{s} + \sqrt{\frac{C_F}{X_F} \left( \frac{k_H P_H D_{H,0}}{B''_H} + \frac{k_{OH} P_{OH} D_{OH,0}}{B''_{OH}} \right)} \]  

where \( RR \) is a function of temperature. Although this method generally does not produce very accurate results, it does predict data trends.

2.3 Combustion and Quenching in Particulate Clouds

In order for a flame to propagate, the energy released in the flame front due to the chemical reaction must keep the temperature of the reaction zone high enough to sustain the reaction. If heat loss to the surroundings becomes too great, the temperature of the reaction zone must decrease. The result of the temperature drop is a decrease in the reaction rate, which in turn reduces the heat output. The temperature will quickly drop below the ignition temperature and the flame will be quenched.

A common parameter for quantifying the above phenomenon is quenching distance \( (d_q) \). The quenching distance is defined as the distance between two
plates that results in the heat production \( \dot{q}_R \) exactly equals the heat loss \( \dot{q}_L \). The heat generation and heat loss by gas phase conduction terms are respectively:

\[
\dot{q}_R = \phi(RR)(Ad)Q_R
\]

\[
\dot{q}_L = kA \frac{dT}{dx}
\]

where \( \phi \) is the stoichiometric mole fraction of the combustible mixture, \( A \) is the area of contact between the flame and the wall for heat loss, and \( Q_R \) is the heat of reaction per mole of the stoichiometric mixture. Therefore, quenching distance \( \frac{c}{d} \) is the minimum distance between two plates, for a given mixture, through which a flame can propagate.

Many other aspects of quenching have been studied as well. Ezekoye and Greif [1993] conducted a theoretical examination of laminar premixed two-dimensional flame quenching. They utilized a finite difference method to compare and contrast head-on and sidewall quenching. The behavior of the systems was modeled by solving the equations for conservation of mass, species, and energy in one dimension. Initially, one edge of the computational domain was set to the burned gas temperature and the rest of the domain was set to the unburned gas temperature. For two dimensional quenching an ignition temperature had to be specified to constrain the reaction. For both cases, by examining the heat transfer
to the boundaries to the system the burning velocities and flame temperatures were similar to experimental values.

Studies on quenching by endothermic reactions have been studied by Lazarovici et al. [2002] and Simon et al. [2002]. Two types of behavior can be supported in this system. They determined the type of behavior that develops depends most strongly on only two factors-the heat loss due to the endothermic reaction relative to the heat generation due to the exothermic combustion of the fuel, and the rate of consumption of the inhibitor relative to the rate of consumption of the fuel.

Kim [1986] investigated the ignition of propane/air mixtures within a suspension of copper particles. He found that for a given propane/air mixture and copper particle diameter there was a limiting particle number density beyond which the mixture would not ignite. Additionally, when the logarithm of the limiting particle number density was plotted versus the logarithm of the particle diameter the result was a line with a slope of approximately -2. Yu [1983] developed correlations for quenching and ignition energy of EPS suspensions of copper particles and propane/air mixtures. He identified the importance of the parameter $N_d^2$ involving particle concentration and size in correlating his combustion data.

The study of the dust cloud combustion is not new. Nusselt [1924] investigated the phenomenon. Through his studies of pulverized coal combustion he determined the burning process of a single particle is influenced by several
regimes, one of which was the diffusion of oxidizer over the surface of the particle. Also, in large dust clouds, radiation heat transfer plays a significant role.

More recently, Kim [1986] investigated the combustion process in suspensions of aluminum spheres in air. He utilized an electrostatic suspension to determine the spark ignition energy required for various particle number densities of aluminum in air. He determined at lean mixtures that a relatively high energy is required.

As the particle number density is increased, the required ignition energy decreases until it reaches a minimum value, and then increases again as the rich limit is approached. Kim [1989] also studied the quenching distances of aluminum/air mixtures. He found quenching distance to similar manner, decreasing initially as aluminum concentration was increased. Then once a critical concentration was reached, the quenching distance increased again.

Particle size also played a significant role in the quenching behavior. As particle size was increased, both the critical concentration and the minimum quenching distance increased accordingly.

Kim [1989] also examined the burning velocity of aluminum/air mixtures in an EPS, shown in Figure 3. Various concentrations of aluminum particle from 12.5 to 1.2μm were suspended then the mixture was ignited. The position of the flame front was measured utilizing a high speed camera at 30 frames per second. It was
observed that initially the burning velocity was very high for all mixtures, likely due to the ignition energy of the spark, then decreased. The burning velocity stabilized after a few milliseconds and proceeded outward at a nearly a constant rate. It was also observed that there was a critical particle concentration for each size. As the concentration deviated from that critical value in either direction the burning velocity decreased. It was also observed that the critical concentration increased as particle size increased.

More recently, Shoshin and Dreizin [2002], developed a devise for creating an aerosol jet for metal particles in the range of 1μm to 1 mm similar to an EPS flame system first used by Colver and his student [Colver et. al. 2004]. Particles were lifted electrostatically, then carried by an aerosol carrying gas. As the particles were ejected from the top of the system, they were heated by radiation heat transfer. By measuring the streaks from the hot particles, as seen in Figure 4, the flame velocity could be determined by equating the flame velocity as equal in velocity and in the opposite direction as the incoming fuel. For 10-14μm aluminum spheres the measured burning velocity was 30 cm/s, for 17-30μm aluminum particles the velocity was 15 cm/s.
Figure 3: Burning velocity vs. particle concentration of three sizes of aluminum spheres in air [Kim, 1989].
Figure 4: An image of an aluminum aerosol flame showing streaks of particles entering flame zone [Shoshin and Dreizin, 2002]
Chapter 3

Experimental Design and Calibration

3.1 Overall Experimental Design and Setup

Various methods can be used to measure burning velocities. For pure gas combustion these processes have shown a great degree of uniformity. However, in powder combustion, results from the different methods are rarely similar or reproducible. Several methods are commonly used but the primary methods involve a variant of a plug-style pneumatic powder injection system or a Bunsen-style burner. In both methods, significant variations in suspension concentration and velocity can occur within the individual tests as well from one test to another (for example, see Kolbe [2001], Huang et al [2006], Chen and Fan [2005], Eapen et al. [2004], and Goroshin et al. [1996]).

The EPS unit designed by Cotroneo and Colver [1978], Colver and Howell [1978], and Colver [1976] {et al.} has shown to exhibit uniform and steady particle concentration [Greene, 2004] as well as uniform particle velocities [Eimers, 2002]. By utilizing the increased ionization that occurs near a flame front as well as the temperature sensitivity of conduction on combustion products, Lawton and Weinberg [1969] developed a method of measuring flame front velocity. Their method was applied to the present EPS system with a minimal alteration.
3.2 EPS Chamber Design

Previous EPS experiments have used either an open or an enclosed chamber. While the open chamber design allows greater flexibility for height adjustment as well as diminishing the possibility of edge spark, the design was abandoned due to the difficulty in maintaining a consistent particle concentration. The open system provides a uniform suspension concentration with regard to height, but over time particle-particle and particle-electrode interactions cause outward diffusion, changing the size of the suspension cylinder and eventually losing particles off the sides of the electrodes. Therefore, a closed chamber was selected for this study.

It was also decided that the flame front velocity would be measured by measuring current flow through the flame front. To accomplish this, the lower electrode was divided into smaller sections which could be individually monitored to determine current flow. The flame velocity is then determined from the differential distance divided by the differential time. The initial circular plate design, shown in Figure 5, was divided into a central spark receiving area and three concentric circles. Each concentric circle was then divided into thirds to allow for three individual measurements to be taken for a given radius during each test.

Figure 6 shows the upper electrode used initially, which was taken from a previous experiment. This electrode allowed a great deal of flexibility in height adjustment; however, the design allowed significant particle blow-by as well as having a high incidence of edge-spark. Consequently, a second upper electrode,
in Figures 7 and 9, was constructed that sandwiched a cut-down glass cylinder rather than being placed inside the taller glass cylinder. The upper electrode was also given a central spark area that was electrically isolated from the rest of the upper electrode. In addition, the lower electrode, in Figures 8 and 10, was redesigned to include an isolated outer safety ring in addition to the previously designed spark receiving area and three subdivided concentric circles. This allowed the possibility of edge-spark occurring without damaging the data acquisition system (DAQ).

In addition to the circular rig, a linear rig was developed (Figure 12 and Figure 13). The design considerations were the same above; however, instead of having the system centrally spark-ignited the system could be manually ignited on one end. In addition the linear rig allowed the measurement of burning velocity with limited distortion from the expanding product gases.

3.3 EPS Circuit Design and Data Acquisition

Two significant issues had to be addressed in the high voltage and DAQ circuits. The first was that two voltage levels were required to perform this test, one to set the suspension voltage and one to trigger the spark. To address the first issue, it was initially attempted to bypass the problem by changing the height of the electrode point. This approach proved unsuccessful because as the distance between the electrode point and the flat electrode plate increased the
electric field was increasingly altered. This resulted in a non-uniform particle suspension that “chased” particles to the edges of the chamber.

A second design that was attempted was to utilize two voltage sources connected in parallel with the chamber as shown in Figure 14. This allowed the two voltages to be set individually. However, due to subsequent equipment failure, this method had to be abandoned.

To produce a similar effect as the two voltage source, the circuit in Figure 15 was created. Because resistors were wired in parallel to the chamber, the capacitors and the chamber were at different voltages.

In order to spark the system with the above circuit, the switch was closed to raise the chamber voltage to that of the capacitor voltage. However, the chamber bypass line also resulted in a low time constant for the circuit. The result was that when the switch was closed the chamber voltage did spark, but the initial voltage setting was lost.

The final circular circuit design, Figure 16, utilized a similar chamber bypass line and a resistor bypass line as in the previous circuit (Figure 15). Again, this allowed the capacitor and the chamber to be at separate voltage levels. Also, the problem with the delay in the voltage rise of the chamber was eliminated.

For the linear circuit the chamber and the capacitor could be kept at the same voltage level because the system was not spark-ignited.
Figure 5: Initial EPS chamber base with central spark receiving area and three sets of three concentric electrode cells.

Figure 6: Initial EPS chamber with base from above and adjustable-height upper electrode.
Figure 7: Final EPS chamber upper electrode with central spark area.
Figure 8: Final EPS chamber upper electrode with central and edge spark areas.
Figure 9: Final EPS chamber top with central spark area.
Figure 10: Final circular EPS chamber base with central spark receiving area and edge spark collection region.
Figure 11: Final EPS chamber test setup.
Figure 12: Linear chamber segmented electrode.
Figure 13: Linear rig test setup with segmented upper electrode.
For simplicity the circuit developed for the circular chamber was used, however the switch and the high-voltage diode were removed as shown in Figure 17.

A second design issue was the DAQ system. The available data acquisition card had a ±10 V limit. This proved to be a problem when incorporated in the circuit having a 50 kV voltage source. While it is relatively simple to “burn off” the excess voltage, the spark will still damage the system.

While the spark is relatively localized, any deviance of the discharge to an adjacent electrode segment could result in damage to the DAQ and the computer. To solve this problem, a 3.3V zener diode was connected to “cap off” the voltage across the data resistors as shown in Figure 18.

A 1.1 GHz PC with LabVIEW software and a National Instruments PCI-6036E data acquisition card was used for data collection and processing. This program collected the voltage data for the nine resistors connected to sections of the lower chamber electrode shown in Figure 18. By utilizing the voltage rise graph (with respect to time) as well as the locations of the electrode sections, the burning velocity is calculated.

3.4 Gas Flow Calibration

Gas flow into the linear EPS chamber was adjusted through a control valve and rotameter assembly. A rotameter measures flow based on the variable area principle.
Figure 14: Second EPS circuit diagram utilizing two voltage sources.

Figure 15: Third EPS circuit diagram with one voltage source and chamber bypass line.
Figure 16: Final EPS circuit diagram, including resistor and chamber bypass lines.

Figure 17: Linear EPS circuit diagram, including resistor and chamber bypass lines.
Figure 18: One third of the circular EPS chamber and DAQ diagram, utilizing resistors and zener diodes to measure flame position.
The variable area principle requires three elements: a uniformly tapered tube, a measurement scale, and a float. As flow rate is increased the float is lifted in the tapered tube. The higher the float rises, the greater the area of the annulus between the float and the tube becomes. From conservation of mass, the velocity of the gas around the float is also decreased as the area of the annulus is increased. At some height the weight of the float will be supported by the fluid forces. By utilizing the Bernoulli equation, material properties, and geometry considerations, the fluid flow at that point can be determined to be

\[ Q = CA_{an}(z) \sqrt{\frac{2g}{\rho} \left( \frac{V_f}{A_f} - \rho g h_f \right)} \left[ \frac{1 - \left( \frac{A_{an}(z)}{A_f(z)} \right)^2}{\rho} \right] \]

(32)

where C is a Reynolds number dependant discharge coefficient, \( V_f \) is the volume of the float, \( \rho \) is the density of the fluid, \( \rho_f \) is the density of the float, and \( A_{an}(z) \) is the area below the float and \( A_{an}(z) \) is the area of the annulus between the wall and the float at height z.

The rotameters were calibrated utilizing a bubble volumetric flow meter in which a rubber balloon is filled with soapy water attached to the bottom of a glass cylinder. Gas was also injected at the bottom of the cylinder, creating a soap-film bubble. By measuring the diameter and the length of the cylinder and the time required for the soap-film bubble to expand the length of the cylinder the
volumetric flow rate can be determined. Figures 19 and 20 show the rotameter setup used and the resulting calibration curves, respectively.

3.5 Particle Density Calibration

Several methods have been used to measure particle density in EPS systems. These include: scanning the suspension by laser beam attenuation [Kim 1989, Colver and Ehlinger 1988, Colver and Howell 1980, Eimers 2002], current density measurement [Colver and Cotreneo 1978], and count or weight of particles [Colver and Ehlinger 1988]. Due to the added difficulty in measuring the current density, this method was rejected. Additionally, not all particles placed in the chamber were suspended; therefore, the count or weight method was rejected as well.

Particle mass can be determined from the total mass of particles in an EPS cell if all particles are assumed to be suspended. With this assumption the total mass is

\[ W = N \rho_p V_p V_{cyl} \]  

(33)

where \( W \) is the total mass, \( N \) is the particle number density, \( \rho_p \) is particle material density, \( V_p \) is the volume of a single particle, and \( V_{cyl} \) is the volume of the suspension cylinder. By rearranging Eq. (33), the particle number density is

\[ N = \frac{24W}{\pi^2 \rho_p d_p^3 V_{cyl} h} \]  

(34)
where \( d_p \) and \( d_{cy} \) are the diameters of a particle and the suspension cylinder respectively.

The Beer-Lambert Law associates particle number density to laser intensity by

\[
\frac{I_r}{I_i} = \exp(-NlA_c\gamma)
\]

where \( I_r \) is the transmitted laser intensity, \( I_i \) is the initial or unobstructed laser intensity, \( l \) is the path length of the laser through the suspension, \( A_c \) is the cross-sectional area of a single particle and \( \gamma \) is the extinction coefficient, which according to the Mie theory is predicted to have a value of two for particles large compared to the wavelength of the light source [Colver and Ehlinger, 1988].

A Metrologic model ML801-K Neon laser and Metrologic Model 54-540 laser power meter was used to measure the laser intensity at a given height in the EPS cell to calculate the particle number density \( N \). The particle number density with respect to transmitted intensity ratio is for various sizes of particles is given in Figure 21.

### 3.6 Particle Preparation

The copper particles used in this study had a diameter range of 53 to 63 micron with a Sauter mean diameter of 55.6 micron as measured using a sonic sifter. As shown in Figure 22, the copper particles are visually spherical and fell within the above size range when measured using a calibrated microscope slide.
The aluminum particles (spherical) in this study had a diameter range of 30-35 micron and a Sauter mean diameter of 31.5 micron as measured by a sonic sifter. Visually, the aluminum particles in Figure 23 are irregularly shaped, many appearing more like grains of rice than spheres. Although overall, the particles could be considered to fall within the expected ranges, many had one dimension that deviated significantly from the 30-35 micron range.
Figure 19: Triple rotameters setup used to meter and monitor propane or natural gas and air injection rates.
Figure 20: Gas flow rate calibration curves for the middle rotameters shown above for natural gas and propane.
Figure 21: Particle number density curves for various particle diameters as calculated by the Beer-Lambert law.
Figure 22: Copper spheres, 53 to 63 μm diameter range, large divisions 100 μm, small divisions 10 μm

Figure 23: Aluminum particles 30-35 μm diameter range, large divisions 100 μm, small divisions 10 μm
Chapter 4

Results

4.1 Test Setup

The *circular* EPS chamber (Figure 24) was attached to a Hipotronics 0 to 50 kV HV DC power supply to power the chamber circuit and generate particulate suspensions. The chamber parts were cleaned with acetone before and after each test and a glass ring of 10, 12, 15, or 18 mm height was selected. If particles were included in the test they were placed in the EPS test cell and the voltage was increased to the desired setting. Propane and air injection levels were manually adjusted to the desired fuel/air ratio and flow rate through the use of calibrated rotameters. After sufficient time for propane and air levels to stabilize within the EPS chamber, the gas and air mixture was turned off. The LabView data acquisition program was initiated and the system was sparked (Figure 25). The recorded data giving voltage versus time of the wavefront was then examined.

In a similar way, the *linear* EPS chamber was attached to a Hipotronics 0 to 50 kV HV DC power supply. For tests involving particles they were then placed in the EPS test cell and the voltage was increased to the desired setting. Propane and air or natural gas and air injection levels were adjusted and verified by calibrated rotameters.
Figure 24: Gas combustion test in circular chamber showing spark ignition.
Figure 25: Circular chamber test with lean aluminum suspension before (top) and during (bottom) sparking process, without ignition.
Sufficient time was allowed for the gas levels to stabilize within the chamber as well as for particles to diffuse. The LabView data acquisition program was initiated and the chamber was manually ignited. The burning velocity and flame structure was then observed and recorded.

4.2 Results and Discussion

The circular chamber, shown in Figure 24, was tested first. Burning velocity measurements were taken for mixtures from 3.4% to 9.1% propane in air within electric field intensities of 1.5 kV/cm to 4.2 kV/cm.

Figure 26 shows real time data of voltage spikes resulting from the flame passing over different (ground) plate electrode segments shown in Figure 8 as it expands outward in the propane/air. From the data it is possible to utilize the flame conductivity to complete the high voltage circuit as designed. The pattern of the voltage spikes (Figure 26) is observed to be consistent with expected flame propagation behavior, that is, with the voltage rises experienced for the segments closest to the center first, then expanding outward. Additionally, all segments at a given radius experienced a voltage spike at similar times.

Figure 27 is a plot of the burning velocity data taken with the circular rig for propane/air mixtures. The data provided by the circular chamber was difficult if not impossible to interpret. The scatter in the burning velocity measurements too large for the measurements to be of any value, with burning velocity measurements ranging from 100 to 900 cm/s for the almost all tested mixtures.
Figure 26: Output of data acquisition file showing voltage spikes for circular chamber during a 4.65% propane run with 5.0 kV/cm electric field strength. Inner, middle, and outer cells refers to the position of the electrodes being monitored.
Figure 27: Circular EPS rig data showing wide variation in measured burning velocities of propane-air mixtures for different runs, where inner, middle, and outer refer to the position of the concentric electrodes.
One reason is the flame is pushed forward by the hot gasses that are produced in the center of the chamber by the flame itself. Another difficulty is that the pressure in the chamber is not consistent throughout the duration of the test.

For all but the very rich or very lean mixtures the top of the chamber was lifted off the chamber by the pressure of the expanding gas.

By examining Equations (24)-(26), it becomes apparent that an increase in pressure results in an increased burning velocity. Both reasons caused the measured velocity to be extremely fast. Since the voltage was not measured continuously, but instead could only be sampled at discrete points in time, the increased velocity also increased the uncertainty in the measurements. For many data runs, the time required for the flame to travel the length of a segment was less than the sampling time. The result was an uncertainty greater than the measured velocity.

The linear chamber, shown in Figure 28, was also tested. Burning velocity measurements were taken for mixtures from 3.5% to 10.1% propane in air as well as mixtures from 5.0% to 14.2% natural gas in air within electric field intensities of 0.6 kV/cm to 6.1 kV/cm. Burning velocity measurements were also taken for suspensions of 9.3 to 63.1 particles per mm$^3$ for 53-63μm copper particles in a 9.3% natural gas mixture and 12.4 to 50.5 particles per mm$^3$ for 30-35μm aluminum particles in an 11.3% natural gas mixture.
The linear rig, shown in Figure 28, had an added benefit of being able to see the structure of the flame as it traveled the length of the EPS test section. Also, one end of the linear test section were open to ambient conditions, therefore, atmospheric pressure was maintained throughout the duration of the test. Burning velocity measurements were taken for propane in air mixtures for the range from 3.4% to 9.1% propane with ignition occurring in the range from 4.6% to 8.0% propane. At mixtures of 4.6% propane the observed the flame had a crescent shape as seen in Figure 29, with the upper edge trailing the lower edge. The color and brightness was relatively uniform throughout the flame front. As shown in Figure 30, as the percentage propane (in air) was increased to a 5.8% mixture the lag between the upper edge and the rest of the flame increased, as did the observed velocity. The flame still maintained its uniformity in color and brightness. When the propane concentration was further increased to 6.9% the visually smooth flame front developed a circling, churning motion and the flame became visibly turbulent with the appearance of the flame collapsing in on itself (Figure 31). At the rich limit of the data (8.0% propane) the flame stabilized back to a laminar profile; however, at the rich limit the lower edge trailed the upper edge (Figure 32). Vertical lines of various shades of blue could be easily seen within the flame front as well.

The propane-air burning velocity measurements taken in the circular rig were

---

2 The flammability limits are 2.2 to 9.5 in propane-air mixtures [Lewis and von Elbe, 1961], however, the tests of 3.4% and 9.1% propane did not support flame travel for the length of the test section.
repeated in the linear EPS chamber with much greater success. Because the linear chamber was open at one end, the expanding gasses could escape instead of pushing the flame forward. This also allowed the chamber to remain at atmospheric pressure throughout the duration of the test. As shown in Figure 33, the burning velocity at the lean end on the tested range (4.6% propane) was measured to be approximately 94.8 cm/s. When the propane concentration was increased to 5.8% the burning velocity increased to an average value of 161.4 cm/s. When the propane concentration was increased further the burning velocity decreased dramatically to 64.7 cm/s. At the rich limit of the data collected (8.0% propane) the velocity had decreased further to 64.7 cm/s.

The curve of the measured burning velocities follows the expected shape, from Lewis and von Elbe [1961], for the burning velocity of propane in air, reaching a maximum value at a value close to stoichiometric, then decreasing as the propane level is either increased or decreased. Each concentration was also tested under a variety of electric field intensities. Using the linear EPS rig, Figure 35, shows that electric field intensity has little effect on the measured burning velocity.

In a similar manner mixtures of natural gas and air were also tested. The data collected in the linear EPS rig for natural gas and air mixtures also behaved as expected, with the maximum burning velocities (137.8 cm/s at 11.3% natural gas and 148.9 cm/s at 9.1% natural gas) near stoichiometric.
Figure 28: Linear rig with natural gas and air flame.
Figure 29: Flame front of 4.6% propane mixture with top edge of flame font trailing bottom edge.

Figure 30: Flame front of 5.8% propane mixture with top edge of flame font trailing bottom edge.
Figure 31: Flame front of 6.9% propane mixture with visually turbulent motion.

Figure 32: Flame front of 8.0% propane mixture with top edge of flame font leading bottom edge.
Figure 33: Linear rig burning velocity data for propane and air mixtures.
Figure 34: Linear rig burning velocity data for propane and air mixtures.
Burning velocity of propane and air mixtures

Figure 35: Measured burning velocities showing small effect of electric field intensity; linear EPS rig.
Figure 36: Ratio of measured vs. laminar burning velocity from Lewis and von Elbe [1961] for propane and air mixtures in the linear rig.
Figure 37: Ratio of measured vs. laminar burning velocity from Lewis and von Elbe [1961] for natural gas and air mixtures in the linear rig.
At either the lean or rich limits the burning velocity decreased dramatically (48.8 cm/s at 6.7% natural gas and 48.8 cm/s at 13.4% natural gas).

As shown in Figures 36 and 37 the measured burning velocities for both mixtures of propane and air as well as natural gas and air were several times the expected burning velocity from Lewis and von Elbe [1961] for a laminar flame. Two factors likely contributed to this result; an increase in area due to flame curvature and turbulence.

The increase in area should be accounted in a similar manner to the transparent-tube method set forth in Kuo (1986). The propagation velocity of a flame front relative to the unburned gas is equal to the laminar burning velocity multiplied by an area factor. The area factor is the area of the flame divided by the cross sectional area. For the mixtures tested the area ratios were determined from pictures to be between 1.2 for lean mixtures and 3.0 for rich mixtures.

The remaining difference between measured and predicted values for burning velocity are likely due to turbulence. At low levels of turbulence the flame structure may still appear smooth; however, burning velocity is increased. The ratio of turbulent to laminar burning velocities can be approximated by the formula [17]

\[
\frac{\bar{V}_T}{\bar{V}_L} = \left( \frac{\alpha_t}{\alpha_L} \right)^{\frac{3}{2}}
\]  

(36)
where the ratio of molar diffusivities \( \alpha_T / \alpha_L \) can be determined through turbulence models \([16, 17]\).

As turbulence is increased, the flame structure transitions to a wrinkled reaction sheet. The burning velocity of a wrinkled reaction sheet is often 3 to 5 times the laminar burning velocity where

\[
\overline{V_T} A_S = \overline{V_L} A_W
\]  

(37)

if \( V_T \) is the turbulent burning velocity, \( A_S \) is the smooth flame area, and \( A_W \) is the area of the wrinkled reaction sheet \([16,17]\). This is also confirmed experimentally for ethane flames by Savarianandam and Lawn [2006]. By utilizing geometric approximations it can be shown that

\[
\overline{V_T} = \overline{V_L} + C \overline{V'}
\]  

(38)

where \( C \) is a proportionality constant, usually between 1 and 2, and \( \overline{V'} \) is the turbulent intensity. If the wrinkling becomes so significant that the flame may surround pockets of unreacted mixture. The burning velocity in this case may actually decrease. An empirical fit

\[
\overline{V_T} = 6.4 \overline{V'} \left( \frac{\overline{V'}}{\overline{V'}} \right)
\]  

(39)

can be used as an approximation \([17]\).
The burning velocity of natural gas and air mixtures were measured in the presence of a suspension of 53-63\(\mu\)m copper particles and an electric field intensity of 3.66 kV/cm using the linear EPS rig in Figure 26. This EPS chamber produced a suspension that was visually uniform. One data set was taken for a uniform suspension throughout the length of the chamber (Appendix D). A second data set was taken when excess particles were placed on one side of the chamber and allowed to diffuse down the length of the chamber (Appendix E). At low particle number densities the measured burning velocity showed a great deal of scatter. However, the majority of the measurements seem to indicate an increase in the burning velocity compared to the burning velocity measurements taken for similar mixtures of natural gas and air mixtures, as shown in Figure 38. The burning velocity appears to peak in suspensions around 2 particles per cubic millimeter. At this concentration the burning velocity is over 2-1/4 times the burning velocity of a similar mixture of natural gas and air. As the particle number density is increased beyond 2 particles per cubic millimeter the burning velocity decreases rapidly, becoming equal to the burning velocity without the suspension at around 3.4 particles per cubic millimeter. Above 4 particles per cubic millimeter the burning velocity with suspension was approximately half that of a non-suspension for the same fuel/air ratio.

In another test, the burning velocity of a 9.1% natural gas in air mixtures was also measured in the presence of a suspension of 30-35\(\mu\)m aluminum (combustible) particles using the linear EPS rig in Figure 28. As shown in Figure
39, for the majority of the range tested the aluminum particles increased the burning velocity of the natural gas-air mixture. Below 25 particles per mm$^3$ the measured burning velocity appeared relatively constant, at around 170 cm/s, with a maximum measured burning velocity of 190 cm/s. This was a small deviation from the burning velocity of an equivalent mixture of natural gas and air, at 150 cm/s. In the range of 25 to 42 particles per mm$^3$ the data splits into two distinct categories. Several points maintain the burning velocity of around 170 cm/s, or less than 15% above the non-suspension burning velocity. The second category is the points where the flame propagation appears to be enhanced significantly by the aluminum powder. Several points were taken with burning velocities of above 280 cm/s, almost double the non-suspension burning velocity. These points seem to indicate the flame is being driven by aluminum ignition. Above 45 particles per mm$^3$ the measured burning velocity slows again and is less than the measured burning velocity for the equivalent natural gas and air mixture.
Figure 38: Linear EPS rig burning velocity data for a 9.3% natural gas and air mixture with copper particles and an electric field intensity of 3.66 kV/cm.
Figure 39: Linear EPS rig measured burning velocity of an 11.3% natural gas and air mixture with aluminum powder and an electric field strength of 3.66 kV/cm.
Chapter 5

Summary, Conclusions and Recommendations

5.1 Summary

Flame propagation velocities of various concentrations of propane and natural gas were measured using both circular and linear EPS chambers. The trends of measured propagation velocities were compared to theoretical laminar burning velocities. Measured velocities were larger than the predicted laminar burning values based on Lewis and von Elbe [1961]. Although for most tests the flame structure appeared to be relatively laminar, turbulent effects could explain differences between theoretical laminar and measured values.

Flame propagation velocities of various concentrations of natural gas with copper spheres were measured. At low concentrations of copper spheres the propagation velocity was increased throughout the range of natural gas concentrations. As the particle concentration was increased the flame propagation velocity decreased. At high concentrations of particles, the measured velocity was lower than the measured velocity in the absence of particles.

Clouds of aluminum particles in natural gas and air mixtures were also combusted and flame propagation velocities measured. Difficulties in data
acquisition limited the information collected; however, initial results suggest a propagation velocity greater than in comparable mixtures of natural gas and air.

5.2 Conclusions

1. Two designs for EPS combustion rigs (circular and linear) were successfully developed to study flame propagation velocities in combustible gas mixtures with/without inert or combustible powders. Data suggest the electrical current method can give reproducible results by sensing flame ionization in both single and two phase combustible mixtures. The EPS method is especially well suited for dispersing powders.

2. Although past studies have shown electric field intensities have strong effects on flame shapes, data collected has shown no effect of electric field intensity on burning velocity.

3. Data at low concentrations show that inert particles may initially increase the flame propagation velocity of premixed gases. As the particle concentration is increased the propagation velocity subsequently decreases. At high concentrations propagation velocities may be lower than the velocity without quenching powder.

4. The propagation velocity of suspensions of aluminum particles in natural gas/air mixtures was measured. At both low and high particle number
densities the flame propagation velocity was found to be higher than for a combustible gas mixture with the same equivalence ratio.

5.3 Recommendations

- Circular EPS test cells having larger dimensions than tested here could be utilized to investigate flame stretch effects on burning velocity.

- EPS burning velocity tests should be expanded to include a wider range of electric field intensities to determine the effect of particle velocity for combustible suspensions.

- EPS burning velocity tests should be conducted in a microgravity environment to expand the range of possible particle relative velocities and limit the buoyant effects.

- Burning velocity data in this study support the use of the EPS test method as a test standard both in 1-g and microgravity conditions.

- Burning velocity measurements collected over a wide range of temperature and concentration conditions could be used to determine constants in Arrhenius relationships for the reaction rates of metallic powders.
• Burning velocity measurements should be extended over a wider range of particle concentrations and fuel/air ratios to further explore the effects of particle quenching.

• Burning velocity measurements should be made over a wide range of conditions to further explore the effects of quenching powders. Measurements should also be made to determine a *quenching condition*, i.e., the critical powder concentration above which a flame cannot propagate.
## Appendix A: Experimental Data-Propane in Circular Rig

<table>
<thead>
<tr>
<th>File</th>
<th>Propane</th>
<th>Air</th>
<th>Voltage</th>
<th>Glass</th>
<th>Temperature</th>
<th>RH</th>
<th>Rotameter (kV)</th>
<th>Rotameter (kV)</th>
<th>Source Mm</th>
<th>Chamber Bulb (F)</th>
<th>Bulb (F)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>719061031</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>7.5</td>
<td>15</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061032</td>
<td>5</td>
<td>10</td>
<td>14</td>
<td>7</td>
<td>15</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061033</td>
<td>5</td>
<td>10</td>
<td>13</td>
<td>6.5</td>
<td>15</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061034</td>
<td>5</td>
<td>10</td>
<td>17.5</td>
<td>8.75</td>
<td>15</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061413</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>7.5</td>
<td>15</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061800</td>
<td>13</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75</td>
<td>68</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061805</td>
<td>6</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75</td>
<td>68</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061810</td>
<td>6</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75</td>
<td>68</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>719061815</td>
<td>6</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75</td>
<td>68</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061140</td>
<td>6</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061145</td>
<td>6</td>
<td>15</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061150</td>
<td>5</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061155</td>
<td>6</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061200</td>
<td>6</td>
<td>15</td>
<td>22</td>
<td>11</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061205</td>
<td>6</td>
<td>15</td>
<td>24</td>
<td>12</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061210</td>
<td>6</td>
<td>15</td>
<td>26</td>
<td>13</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061211</td>
<td>6</td>
<td>15</td>
<td>26</td>
<td>13</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061330</td>
<td>7</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061335</td>
<td>7</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061440</td>
<td>7</td>
<td>15</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>720061445</td>
<td>7</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061450</td>
<td>7</td>
<td>15</td>
<td>22</td>
<td>11</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061455</td>
<td>7</td>
<td>15</td>
<td>22</td>
<td>11</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061500</td>
<td>7</td>
<td>15</td>
<td>24</td>
<td>12</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061505</td>
<td>8</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061510</td>
<td>5</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061515</td>
<td>5</td>
<td>15</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061520</td>
<td>5</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061525</td>
<td>5</td>
<td>15</td>
<td>22</td>
<td>11</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061530</td>
<td>5</td>
<td>15</td>
<td>24</td>
<td>12</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061540</td>
<td>4</td>
<td>15</td>
<td>14</td>
<td>7</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061545</td>
<td>4</td>
<td>15</td>
<td>16</td>
<td>8</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061550</td>
<td>4</td>
<td>15</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061555</td>
<td>4</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061600</td>
<td>4</td>
<td>15</td>
<td>22</td>
<td>11</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061605</td>
<td>4</td>
<td>15</td>
<td>24</td>
<td>12</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061610</td>
<td>4</td>
<td>15</td>
<td>26</td>
<td>13</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061615</td>
<td>4</td>
<td>15</td>
<td>28</td>
<td>14</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061620</td>
<td>4</td>
<td>15</td>
<td>30</td>
<td>15</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720061625</td>
<td>3</td>
<td>15</td>
<td>30</td>
<td>15</td>
<td>18</td>
<td>75.5</td>
<td>68</td>
<td>69</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720620000</td>
<td>3</td>
<td>15</td>
<td>11</td>
<td>5.5</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>720620005</td>
<td>4</td>
<td>15</td>
<td>6</td>
<td>3</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72062010</td>
<td>4</td>
<td>15</td>
<td>7</td>
<td>3.5</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72062015</td>
<td>4</td>
<td>15</td>
<td>8</td>
<td>4</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72062020</td>
<td>4</td>
<td>15</td>
<td>9</td>
<td>4.5</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72062025</td>
<td>4</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>72062030</td>
<td>4</td>
<td>15</td>
<td>11</td>
<td>5.5</td>
<td>10</td>
<td>74.5</td>
<td>68</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Appendix B: Experimental Data-Propane in Linear Rig

<table>
<thead>
<tr>
<th>File</th>
<th>Propane Vol (cm³/s)</th>
<th>Air Rot Vol (cm³/s)</th>
<th>Percent (%)</th>
<th>Voltage (kV)</th>
<th>Temps (F)</th>
<th>RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>72806-1</td>
<td>1.458</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>72806-2</td>
<td>1.458</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>72806-3</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>72806-4</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>2.5</td>
<td>1.25</td>
</tr>
<tr>
<td>72806-5</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>72806-6</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>72806-7</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>7.5</td>
<td>3.75</td>
</tr>
<tr>
<td>72806-8</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>7.5</td>
<td>3.75</td>
</tr>
<tr>
<td>72806-9</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>72806-10</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>72806-11</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>72806-12</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>12.5</td>
<td>6.25</td>
</tr>
<tr>
<td>72806-13</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>72806-14</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>72806-15</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>17.5</td>
<td>8.75</td>
</tr>
<tr>
<td>72806-16</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>17.5</td>
<td>8.75</td>
</tr>
<tr>
<td>72806-17</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>72806-18</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>72806-19</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>22.5</td>
<td>11.25</td>
</tr>
<tr>
<td>72806-20</td>
<td>0.830</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
<td>22.5</td>
<td>11.25</td>
</tr>
<tr>
<td>72806-21</td>
<td>0.830</td>
<td>23.906</td>
<td>Yes</td>
<td>3.36%</td>
<td>25</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>----</td>
<td>-----</td>
<td>----</td>
<td>-----</td>
<td>----</td>
</tr>
<tr>
<td>72806-22</td>
<td>3</td>
<td>0.830</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>3.36%</td>
</tr>
<tr>
<td>72806-23</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-24</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-25</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-26</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-27</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-28</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-29</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-30</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-31</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-32</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-33</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-34</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-35</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-36</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-37b</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-38</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-39</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-40</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-41</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-42</td>
<td>4</td>
<td>1.144</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>4.57%</td>
</tr>
<tr>
<td>72806-43</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-44</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-45</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-46</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-47</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>Document ID</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
<td>Value 4</td>
<td>Value 5</td>
<td>Value 6</td>
</tr>
<tr>
<td>-------------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>72806-48</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-49</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-50</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-51</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-52</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-53</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-54</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-55</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-56</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-57</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-58</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-59</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-60</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-61</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-62</td>
<td>5</td>
<td>1.458</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>5.75%</td>
</tr>
<tr>
<td>72806-63</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-64</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-65</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-66</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-67</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-68</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-69</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-70</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-71</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-72</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-73</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>---</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>---</td>
<td>-----</td>
</tr>
<tr>
<td>72806-74</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-75</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-76</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-77</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-78</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-79</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-80</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-81</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-82</td>
<td>6</td>
<td>1.772</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>6.90%</td>
</tr>
<tr>
<td>72806-83</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-84</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-85</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-86</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-87</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-88</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-89</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-90</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-91</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-92</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-93</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-94</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-95</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-96</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-97</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-98</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>No</td>
<td>8.03%</td>
</tr>
<tr>
<td>72806-99</td>
<td>7</td>
<td>2.086</td>
<td>15</td>
<td>23.906</td>
<td>Yes</td>
<td>8.03%</td>
</tr>
<tr>
<td>Code</td>
<td>Value</td>
<td>Class</td>
<td>Rate</td>
<td>Factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-100</td>
<td>7</td>
<td>No</td>
<td>8.03%</td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-101</td>
<td>7</td>
<td>Yes</td>
<td>8.03%</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-102</td>
<td>7</td>
<td>No</td>
<td>8.03%</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-103</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-104</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-105</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-106</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-107</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-108</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-109</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-110</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-111</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-112</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-113</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-114</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-115</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>17.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-116</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>17.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-117</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-118</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-119</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-120</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>22.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-121</td>
<td>8</td>
<td>Yes</td>
<td>9.12%</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72806-122</td>
<td>8</td>
<td>No</td>
<td>9.12%</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix C: Experimental Data-Natural Gas in Linear Rig

<table>
<thead>
<tr>
<th>Natural Gas</th>
<th>Air</th>
<th>NG</th>
<th>Voltage</th>
<th>Burn</th>
<th>cm³/s</th>
<th>cm³/s</th>
<th>%NG</th>
<th>cm/s</th>
<th>(F)</th>
<th>(F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run #</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>91601</td>
<td>11</td>
<td>20</td>
<td>5</td>
<td>Partial</td>
<td>15.558</td>
<td>6.167</td>
<td>0.284</td>
<td>1.486</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91602</td>
<td>11</td>
<td>20</td>
<td>5</td>
<td>Partial</td>
<td>15.558</td>
<td>6.167</td>
<td>0.284</td>
<td>1.486</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91603</td>
<td>11</td>
<td>6.5</td>
<td>5</td>
<td>No</td>
<td>15.558</td>
<td>1.929</td>
<td>0.110</td>
<td>1.196</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91604</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>No</td>
<td>15.558</td>
<td>1.144</td>
<td>0.069</td>
<td>1.143</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91605</td>
<td>11</td>
<td>10</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91606</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91607</td>
<td>11</td>
<td>10</td>
<td>12.5</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91608</td>
<td>11</td>
<td>10</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91609</td>
<td>11</td>
<td>10</td>
<td>20</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91610</td>
<td>11</td>
<td>9</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91611</td>
<td>11</td>
<td>9</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91612</td>
<td>11</td>
<td>9</td>
<td>12.5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91613</td>
<td>11</td>
<td>9</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91701</td>
<td>11</td>
<td>11</td>
<td>5</td>
<td>No</td>
<td>15.558</td>
<td>3.342</td>
<td>0.177</td>
<td>1.293</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91702</td>
<td>11</td>
<td>10</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91703</td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91704</td>
<td>11</td>
<td>10</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91705</td>
<td>11</td>
<td>10</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91706</td>
<td>11</td>
<td>10</td>
<td>20</td>
<td>Yes</td>
<td>15.558</td>
<td>3.028</td>
<td>0.163</td>
<td>1.272</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91707</td>
<td>11</td>
<td>9</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91708</td>
<td>11</td>
<td>9</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91709</td>
<td>11</td>
<td>9</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>ID</td>
<td>Size</td>
<td>Time</td>
<td>Amount</td>
<td>Speed</td>
<td>Change</td>
<td>Result</td>
<td>Value 1</td>
<td>Value 2</td>
<td>Value 3</td>
<td>Value 4</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
<td>-------</td>
<td>--------</td>
<td>-------</td>
<td>--------</td>
<td>--------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>91710</td>
<td>11</td>
<td>9</td>
<td>20</td>
<td>Yes</td>
<td>15.558</td>
<td>2.714</td>
<td>0.149</td>
<td>1.250</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91711</td>
<td>11</td>
<td>8</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.400</td>
<td>0.134</td>
<td>1.229</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91712</td>
<td>11</td>
<td>8</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>2.400</td>
<td>0.134</td>
<td>1.229</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91713</td>
<td>11</td>
<td>8</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>2.400</td>
<td>0.134</td>
<td>1.229</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91714</td>
<td>11</td>
<td>8</td>
<td>20</td>
<td>Yes</td>
<td>15.558</td>
<td>2.400</td>
<td>0.134</td>
<td>1.229</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91715</td>
<td>11</td>
<td>7</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.086</td>
<td>0.118</td>
<td>1.207</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91716</td>
<td>11</td>
<td>7</td>
<td>10</td>
<td>Yes</td>
<td>15.558</td>
<td>2.086</td>
<td>0.118</td>
<td>1.207</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91717</td>
<td>11</td>
<td>7</td>
<td>15</td>
<td>Yes</td>
<td>15.558</td>
<td>2.086</td>
<td>0.118</td>
<td>1.207</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91718</td>
<td>11</td>
<td>7</td>
<td>20</td>
<td>Yes</td>
<td>15.558</td>
<td>2.086</td>
<td>0.118</td>
<td>1.207</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91719</td>
<td>11</td>
<td>6</td>
<td>5</td>
<td>No</td>
<td>15.558</td>
<td>1.772</td>
<td>0.102</td>
<td>1.186</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91720</td>
<td>11</td>
<td>6.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>1.929</td>
<td>0.110</td>
<td>1.196</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91721</td>
<td>11</td>
<td>7.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.243</td>
<td>0.126</td>
<td>1.218</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91722</td>
<td>11</td>
<td>8.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.557</td>
<td>0.141</td>
<td>1.239</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91723</td>
<td>11</td>
<td>9.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>2.871</td>
<td>0.156</td>
<td>1.261</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91724</td>
<td>11</td>
<td>10.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>3.185</td>
<td>0.170</td>
<td>1.282</td>
<td>78</td>
<td>70</td>
</tr>
<tr>
<td>91725</td>
<td>11</td>
<td>10.5</td>
<td>5</td>
<td>Yes</td>
<td>15.558</td>
<td>3.185</td>
<td>0.170</td>
<td>1.282</td>
<td>78</td>
<td>70</td>
</tr>
</tbody>
</table>
### Appendix D: Experimental Data-Natural Gas and Constant Density

#### Copper Particles in Linear Rig

<table>
<thead>
<tr>
<th>Name</th>
<th>NG</th>
<th>Air</th>
<th>Io</th>
<th>I</th>
<th>la</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>11-8-15-2</td>
<td>8</td>
<td>11</td>
<td>0.93</td>
<td>0.909</td>
<td>0.005</td>
<td>15</td>
</tr>
<tr>
<td>11-8-15-4</td>
<td>8</td>
<td>11</td>
<td>0.78</td>
<td>0.668</td>
<td>0.005</td>
<td>15</td>
</tr>
<tr>
<td>11-8-15-5</td>
<td>8</td>
<td>11</td>
<td>0.78</td>
<td>0.683</td>
<td>0.005</td>
<td>15</td>
</tr>
<tr>
<td>11-8-15-6</td>
<td>8</td>
<td>11</td>
<td>0.88</td>
<td>0.846</td>
<td>0.005</td>
<td>15</td>
</tr>
<tr>
<td>11-8-15-7</td>
<td>8</td>
<td>11</td>
<td>0.855</td>
<td>0.81</td>
<td>0.005</td>
<td>15</td>
</tr>
</tbody>
</table>
Appendix E: Experimental Data-Natural Gas and Variable Density

Copper Particles in Linear Rig

<table>
<thead>
<tr>
<th>NG</th>
<th>Air</th>
<th>V</th>
<th>Ia1</th>
<th>Ia2</th>
<th>Offset</th>
<th>Intensity Without Suspension</th>
<th>Intensity With Suspension</th>
<th>Intensity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-20-1</td>
<td>8</td>
<td>11</td>
<td>20</td>
<td></td>
<td>0.003</td>
<td>0.238</td>
<td>0.747 0.424</td>
<td>0.61 0.419</td>
</tr>
<tr>
<td>B-20-2</td>
<td>8</td>
<td>11</td>
<td>20</td>
<td></td>
<td>0.004</td>
<td>0.272</td>
<td>0.907 0.45</td>
<td>0.58 0.44</td>
</tr>
<tr>
<td>B-20-3</td>
<td>9</td>
<td>11</td>
<td>25</td>
<td></td>
<td>0.004</td>
<td>0.27</td>
<td>0.834 0.468</td>
<td>0.365 0.448</td>
</tr>
<tr>
<td>B-20-4</td>
<td>9</td>
<td>11</td>
<td>25</td>
<td></td>
<td>0.004</td>
<td>0.276</td>
<td>0.85   0.417</td>
<td>0.41 0.408</td>
</tr>
<tr>
<td>B-20-6</td>
<td>9</td>
<td>11</td>
<td>22.5</td>
<td></td>
<td>0.004</td>
<td>0.276</td>
<td>0.732 0.408</td>
<td>0.403 0.407</td>
</tr>
<tr>
<td>B-20-7</td>
<td>9</td>
<td>11</td>
<td>30</td>
<td></td>
<td>0.0045</td>
<td>0.275</td>
<td>0.83   0.4</td>
<td>0.23 0.35</td>
</tr>
<tr>
<td>B-20-8</td>
<td>9</td>
<td>11</td>
<td>22.5</td>
<td></td>
<td>0.005</td>
<td>0.276</td>
<td>0.913 0.395</td>
<td>0.888 0.394</td>
</tr>
</tbody>
</table>
### Appendix F: Experimental Data-Natural Gas and Variable Density

#### Aluminum Particles in Linear Rig

<table>
<thead>
<tr>
<th></th>
<th>Intensity Without Offset</th>
<th>Intensity With Offset</th>
<th>Intensity Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intensity</td>
<td>Suspension</td>
<td>Suspension</td>
</tr>
<tr>
<td>NG Air</td>
<td>V</td>
<td>Ia1</td>
<td>Ia2</td>
</tr>
<tr>
<td>AI-1</td>
<td>9</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>AI-2</td>
<td>9</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td>AI-3</td>
<td>9</td>
<td>11</td>
<td>18</td>
</tr>
</tbody>
</table>
Appendix G: Error Analysis

In every experimental circumstance there will be some uncertainty in the raw data. This uncertainty can be attributed to one or more of three types of errors: illegitimate, systematic, and random errors. Illegitimate errors are errors generally caused by the experimenter. These can include errors in the reading of instruments, incorrectly recording of data, or errors in calculations. Illegitimate errors can generally be reduced by careful and consistent method for verifying and recording experimental procedures and results as well as double-checking calculations. Systematic errors are generally consistent errors and are generally associated with experimental method. These can include improperly calibrated equipment, improperly devised experimental method, or conditions outside valid experimental parameters. Random errors are associated with irregularities within the system. These can include fluctuations within experimental measurements or disturbances within the system. Random errors can be minimized through experimental design; however, they cannot be completely eliminated. Therefore it is necessary to determine the total statistical uncertainty through a propagation of error analysis in order to determine the accuracy and validity of the experimental data [36].

The uncertainty of experimental results depends on the uncertainty of the independently measured quantities. If the independently measured quantities are
distributed around a mean and the distribution is approximately symmetrical the uncertainty (U) of a calculated quantity (Z) can be calculated as [34]:

$$U_Z^2 = \sum_{i=1}^{n} \left( \frac{\partial Z}{\partial Y_i} \right)^2 U_{Y_i}^2$$  \hspace{1cm} (40)$$

where Yi are the parameters, 1 to n, of which Z is a function of. A simplified form of the propagation of error equation results if Z can be expressed by the equation:

$$\left( \frac{U_z}{Z} \right)^2 = a^2 \left( \frac{\partial Y_1}{Y_1} \right)^2 + b^2 \left( \frac{\partial Y_2}{Y_2} \right)^2 + \ldots + m^2 \left( \frac{\partial Y_n}{Y_n} \right)^2$$  \hspace{1cm} (41)$$

and Z can be expressed

$$Z = Y_1^a + Y_2^b + \ldots + Y_n^m$$  \hspace{1cm} (42)$$

The uncertainties of each variable will be evaluated to determine the statistical uncertainty of this experiment.

**Particle Diameter**

The copper particles used in this study were sifted to within the range of 53-63\(\mu\)m and the aluminum particles were sifted to within the range of 30-35\(\mu\)m. However, examination of the particles reveals that some percentage of the particles falls outside sifted range. Therefore, the uncertainty in diameter is chosen to be ±8\(\mu\)m for copper particles and ±4\(\mu\)m for aluminum particles. The
mean diameter for the sieve range was used for each type of particle, 58\(\mu\)m for copper particles and 32.5\(\mu\)m for aluminum.

\[
\left( \frac{U_d}{d_p} \right)_{Cu} = 0.138 \tag{43}
\]

\[
\left( \frac{U_d}{d_p} \right)_{Al} = 0.123 \tag{44}
\]

**Source Voltage**

The voltage source used in this study was a 0-±50 kV DC source. Within that range three voltage range selections were possible 0-10 kV, 0-25 kV, and 0-50 kV. For each test the lowest smallest range that could be supported for the required chamber voltage was utilized. Within the 0-10 kV range the gauge had major indicating ticks for every 2 kV. The major ticks are subdivided into five smaller sections, each of 400 V. The uncertainty was assumed to be the margin of error on reading the dial-1/4 of a minor tick, or 100 Volts. For a required chamber voltage of 2.5 kV the source voltage would be at 5 kV. The resulting uncertainty is defined as:

\[
\left( \frac{U}{V} \right)_{Source} = 0.020 \tag{45}
\]
**Chamber Voltage**

The chamber voltage is a direct result of the source voltage. The source voltage is stepped down through the use of one 100 MΩ resistor before the chamber and another 100 MΩ resistor in parallel to the chamber. The chamber voltage can be calculated as

$$V_{\text{Chamber}} = V_{\text{Source}} \frac{R_1}{R_1 + R_2}$$  \hfill (46)

Therefore the uncertainty of the chamber voltage can be determined as:

$$\left(\frac{U_{V/\mu}}{V}\right)_{\text{Chamber}}^2 = \left(\frac{U_{V/\mu}}{V}\right)_{\text{Source}}^2 + 2\left(\frac{U_{R/\mu}}{R_1}\right)^2 + \left(\frac{U_{R/\mu}}{R_2}\right)^2$$  \hfill (47)

From above the fractional uncertainty of the voltage source is 0.02. Also each of the resistors used had an uncertainty of 1%. Therefore the fractional uncertainty of the chamber voltage is:

$$\left(\frac{U_{V/\mu}}{V}\right)_{\text{Chamber}} = 0.026$$  \hfill (48)

**Particle Number Density**

To determine the particle number density within a suspension the Beer-Lambert law was used. The Beer-Lambert Law relates the ratio of the intensity of transmitted laser light compared to the intensity without the suspension along with
the particle size and laser path length to determine the particle concentration, where

\[ \frac{I_o}{I_i} = \exp\left(-Nl,A,c\right) \]  

(49)

When the above equation is rearranged for \( N \), the particle number density and diameter is used instead of cross sectional area the result is:

\[ N = \frac{41\ln\left(\frac{I_o}{I_i}\right)}{I_i \gamma d^2} \]  

(50)

The uncertainty of the particle number density can then be expressed as

\[ \left(\frac{U_N}{N}\right)^2 = \left(\frac{U_{ln}}{I_i}\right)^2 + \left(\frac{U_{\lambda}}{I_o}\right)^2 + \left(\frac{U_{I_i}}{I_i}\right)^2 + \left(\frac{2U_d}{d}\right)^2 \]  

(51)

where the uncertainty in the length of the laser path is the same as the uncertainty in the width of the chamber. For the linear chamber the width is 70.8±1.0 mm.

\[ \left(\frac{U_I}{I}\right) = 0.014 \]  

(52)

Also the uncertainty in the laser intensity is determined to be the maximum deviation from the mean value output from the laser power meter or 0.04 mW. For an initial transmitted laser power reading of 0.752 mW and a suspension transmitted laser power reading of 0.485 mW the resulting uncertainties become:
Using the fractional uncertainty in diameter for aluminum particles from above the uncertainty in particle number density becomes:

\[
\left( \frac{U_{D}}{\Delta D} \right) = 0.053 \tag{53}
\]

\[
\left( \frac{U_{D}}{\Delta D} \right) = 0.082 \tag{54}
\]

\[
\left( \frac{U_{N}}{N} \right) = 0.200 \tag{55}
\]

**Gas Mixture**

The gas was injected into the system through the use of calibrated rotameters. The uncertainty in the calibration is taken to be 1-C, where C is the R² value taken from the excel worksheet. For propane this was 0.009, for natural gas this was 0.056. For the air the uncertainty was .006. In addition the uncertainty in the height of the ball must be accounted for. For the rotameters used, the minimum differential that could be consistently determined was ¼ mark on the rotameters.

\[
\left( \frac{U_{Q}}{\Delta Q} \right)^2 = \left( \frac{U_{M}}{\Delta M} \right)^2 + \left( \frac{U_{h}}{\Delta h} \right)^2 \tag{56}
\]

\[
\left( \frac{U_{Q}}{\Delta Q} \right)^2 = \left( \frac{U_{M}}{\Delta M} \right)^2 + \left( \frac{U_{h}}{\Delta h} \right)^2 \tag{57}
\]
For a 6.9% propane in air mixture the air rotameters is set to 6 and the air rotameters is set to 15. This results in uncertainties of

\[
\left( \frac{U_Q}{Q} \right)_{\text{air}} = 0.017
\]

\[
\left( \frac{U_Q}{Q} \right)_{\text{fuel}}^2 = 0.042
\]

The fuel mixture (as percent fuel) is given by the equation:

\[
\%\text{Fuel} = \frac{Q_{\text{fuel}}}{Q_{\text{fuel}} + Q_{\text{air}}}
\]

The resulting uncertainty in the fuel mixture, in percent fuel is:

\[
\left( \frac{U_{\%\text{Fuel}}}{\%\text{Fuel}} \right)_{\text{mixture}}^2 = 2 \left( \frac{U_Q}{Q} \right)_{\text{fuel}}^2 + \left( \frac{U_Q}{Q} \right)_{\text{air}}^2
\]

\[
\left( \frac{U_{\%\text{Fuel}}}{\%\text{Fuel}} \right)_{\text{mixture}} = 0.061
\]

**Measured Burning Velocity**

The burning velocity is calculated based on the times of voltage rise for electrodes at given locations. The length of a given electrode is taken to be 50.8±0.2mm. The uncertainty in the time of any individual time data point is taken to be the sampling time-or the time between two discrete data points. For most of
the data collected this was set to 2 ms. Although two discrete data points are required to determine a velocity the time uncertainty can still be taken as the sampling time because the error in measurement will always occur in the time period before the point is taken. For the case when the measured time difference is 35 ms the resulting uncertainty in the burning velocity becomes:

\[
\left( \frac{U_s}{S} \right)^2 = \left( \frac{U_t}{I} \right)^2 + \left( \frac{U_r}{I} \right)^2
\]  \hspace{1cm} (63)

\[
\left( \frac{U_s}{S} \right) = 0.057
\]  \hspace{1cm} (64)
Bibliography


