Analysis of Cornstarch Dust-Air Premixed Flames

The Design and Experimentation of a Dust Combustion Apparatus for the
Combustion of a Cornstarch – Air Mixture

A Major Qualifying Project, to be submitted to the faculty of
Worcester Polytechnic Institute in partial fulfillment of the requirements for the
Degree of Bachelor of Science

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April 30, 2009

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Abstract

Currently NFPA 68 (Standard on Explosion Protection by Deflagration Venting) utilizes a system of explosion hazard classification that relies on a deflagration index; as part of this project we attempted to find a different explosion hazard parameter called the laminar burning velocity. Throughout the project, the group designed and developed a dust combustion apparatus to experimentally determine the laminar burning velocity of a cornstarch-air mixture. The apparatus consisted of an air intake, dust hopper, mixing chamber, burner tube and a vacuum exhaust system and allowed a flame (about 4 to 8 cm long) to stabilize at the burner outlet. The measured laminar burning velocity showed good agreement with data published in literature.

1   Introduction

Worldwide, various industries use a diverse range of dust types. Depending on the process needs of the industry, theses dusts are stored, creating large stockpiles in large silos or compartments. The types of dust range from agricultural, such as cornstarch, to fuel, like coal. In order to make a standard of how to protect facilities from large and dangerous dust explosions, NFPA 68: *Explosion Protection by Deflagration Venting*[1] utilizes a system of explosion hazard classification that relies on a deflagration index. As part of this project, the goal was to find more measureable explosion characteristics that could be used for hazard classification. This study investigates the laminar burning velocity based on concentration of a cornstarch and air dust mixture.

Throughout the industry, there have been a several number of dust explosion incidents which have cost millions of dollars to the industry and many fatalities and injured people. The following chart, adapted from the work of Cédric Venet[2], S.A. Abbasi[3] and T. Abbasi[3], graphically depicts the different types of dusts used in the industry from 1785 until 2003, and the cost of the incidents.
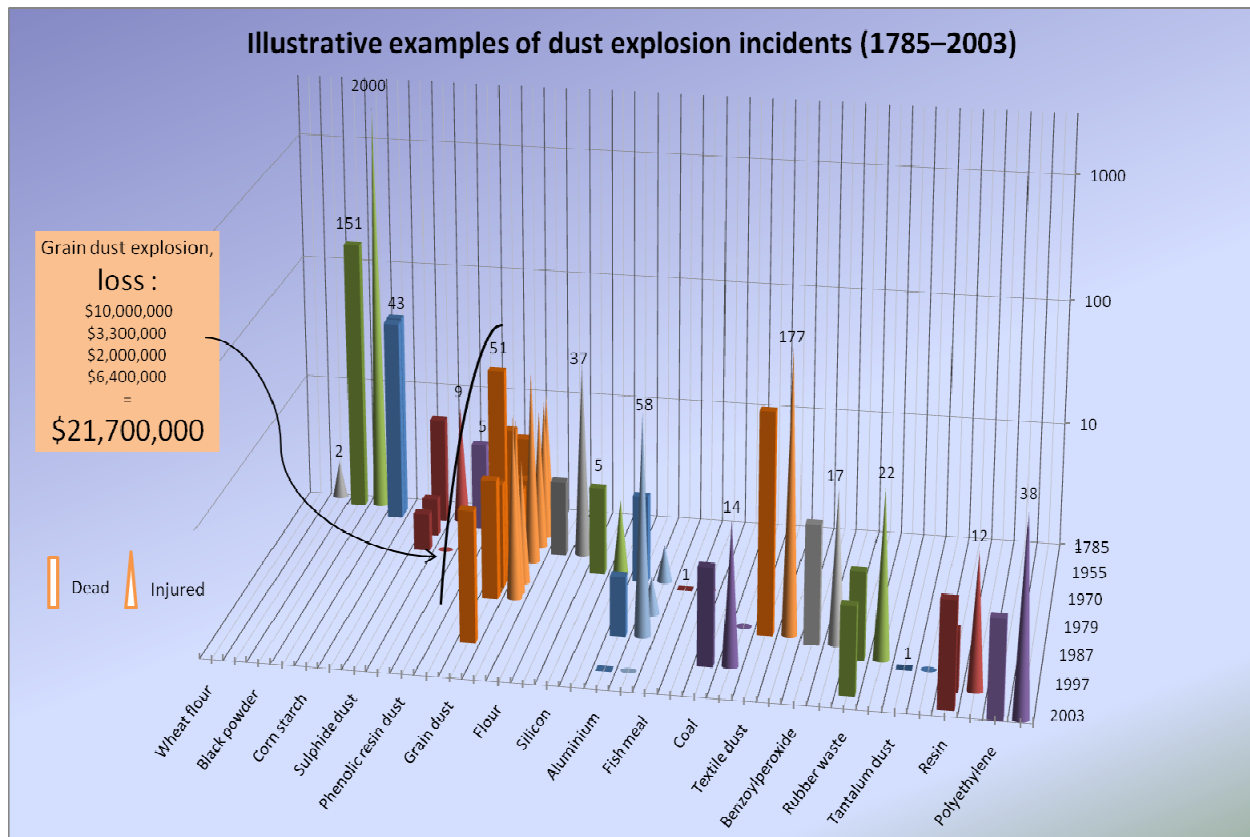
Figure 1- Illustrative examples of dust explosion incidents from 1785 to 2003 displaying types of dust in incidents, cost of incident, and number of deaths and injured victims.

A more specific example of a dust incident occurred on February 7, 2008, where there was a large sugar explosion in an Imperial Sugar factory in Port Wentworth, Georgia. The incident happened one evening in the packaging area of the facility where there were large portions of sugar in the air. The explosion

caused 14 deaths in total, and 42 more injured. In the end, it cost the company as much as 15.5 million dollars.

The incident at the sugar factory in Georgia is only one of many types of incidents that have occurred due to excessive amounts of dust in factories or warehouses. Figure 2 shows the different types of commercial products that use dust in one way or another and what percent of total recorded dust explosions are caused by each product.
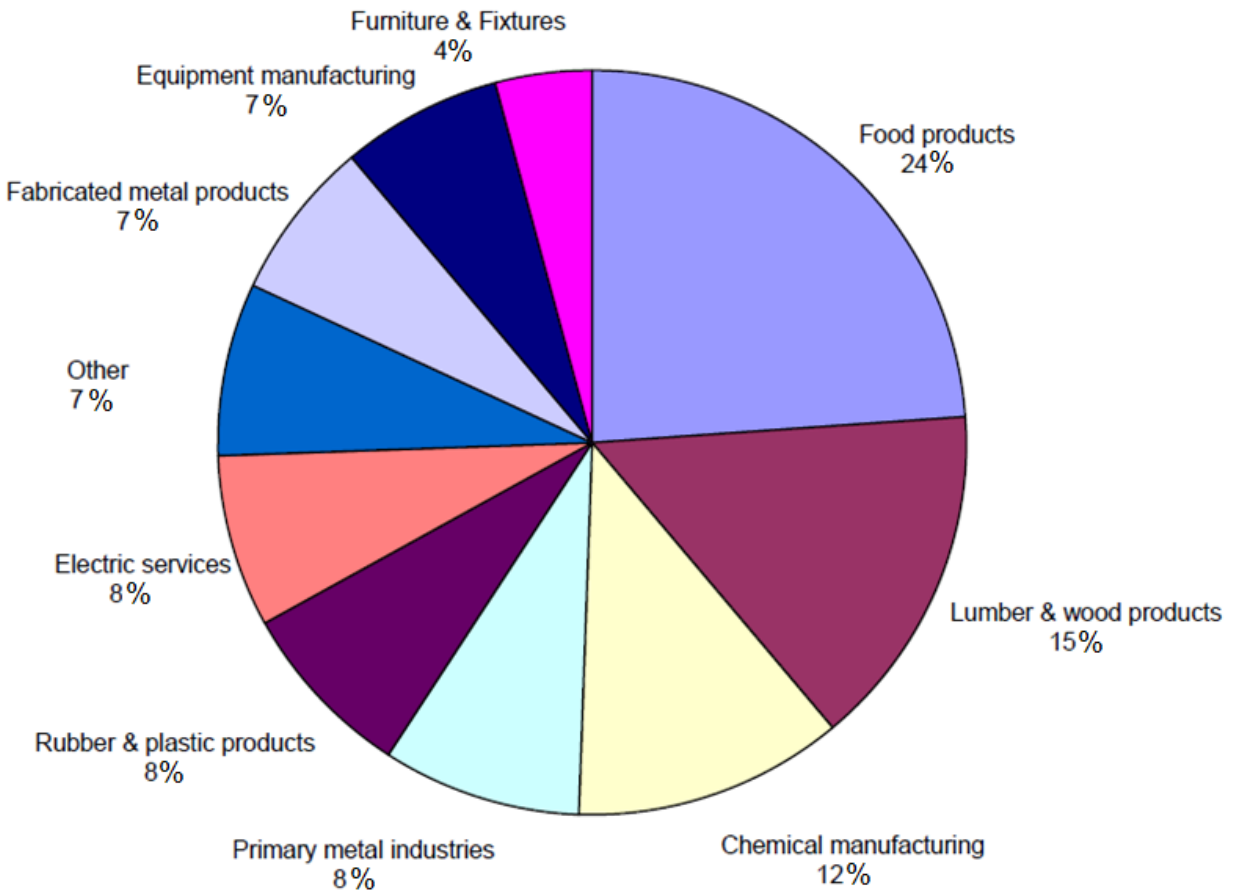
Figure 2- Percent of total dust incidents in each industry. (Source: US Congress)

Originally we were planning to use poly(methyl methacrylate) (PMMA) for the dust mixture. However, due to the availability and cost of PMMA we decided to use corn starch instead. Cornstarch is widely available and very inexpensive. Incidents relating specifically to cornstarch are rare however; when suspended in air it acts similarly to other natural product dusts such as flour, sugar and grain. All of these natural products are used worldwide in various industries, so by basing our research on cornstarch we would be able to widely apply our results.

2   Dust Hazard Rating Used by NFPA 68

In NFPA 68: Standard on Explosion Protection by Deflagration Venting, a standard of classifying dusts based on their deflagration characteristics is brought to attention. The characteristic which is used throughout the document to classify the dusts is the K_{st} value of the dust. The K_{st} value of the dust is the maximum change in pressure over a change in time for a dust cloud and can be defined by the following equation found in ATSM E 1226-05[5].

$$K_{st} = V^{\frac{1}{3}} \frac{dP}{dt}_{max} \qquad (1)$$

Where:

Kst = Deflagration Index [bar m/s]
V = Volume [m3]
P = Pressure [bar]
t = time [s]

The K_{st} value is initially recorded at atmospheric pressure. To determine the value, a cloud of dust is formed in a closed spherical or cylindrical combustion chamber at least 20 liter in volume. Ignition of the dust-air mixture is then attempted after a specified delay time. As a result of this the pressure-time curve is recorded.
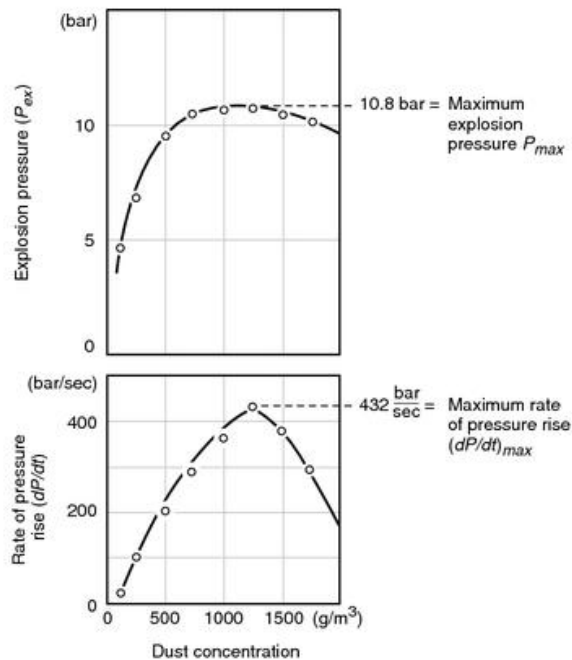

Figure 3- Variation of Deflagration Pressure and Deflagration Index with Concentration for Several Dusts

(Source: ASTM E1226-05[5])

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For cornstarch, maximum pressure is about 10.3 bar and the K_{st} value is 202, making it a St-2 hazard class. Below is a table of the different hazard classes and how they are defined by the K_{st} value.

Hazard Class	K_{st} (bar*m/s)	P_{max} (bar)
St-1	≤ 200	10
St-2	201-300	10
St-3	> 300	12

Table 1- Hazard Class classification from NFPA 68: Explosion Protection by Deflagration Venting[1]

Measuring the different K_{st} values takes extensive testing to determine at what point the maximum pressure is achieved. As the concentration of dust in a chamber is slowly increased, the rate of pressure rise changes and is graphed accordingly. Once the pressure begins to decrease as the concentration keeps increasing, the maximum rate of pressure rise is found and can be correlated to the maximum explosion pressure, or P_{max} of the dust system. This complex model is used to measure the maximum explosion pressure and eventually correlates to the K_{st} values and the Hazard Class of each dust found in tables in NFPA 68. The K_{st} value is also used by the NFPA to create a requirement for vent sizing during deflagrations.

Information provided in NFPA 68 standard helps companies in the industry protect their facilities based on how hazardous the dust is while mixed with air. The main focus of this project is to find an easier value to measure the volatility of the dust and a way to correlate that to deflagrations. The laminar burning velocity of the flame can be measured easily based on an equation using the flame angle or an equation relating flame height, radius, and volumetric flow rate. Both of these equations have been referenced from Strehlow[6] and are explained below

$$S_u = U * \sin \alpha \qquad (2)$$

$$S_u = \frac{2U}{\pi r \sqrt{l^2 + r^2}} \qquad (3)$$

Where:
S_u = Laminar Burning Velocity [m/s]
U = Volumetric Flow Rate [m³/s]
α = Flame Angle [degrees]
r = Radius of Burner Tube [m]
l = Height of Flame [m]

Using the information collected, the laminar burning velocity of the flame can be calculated and related to the concentration of the dust in the air. The goal is to correlate the laminar burning velocity of the dust mixture to the volatility and reactivity of the dust, and to use this in place of the complex K_{st} value utilized by the NFPA.

3   Experimental Set-Up

The most important component of our research was the apparatus. Our apparatus needed to consistently add the cornstarch into a stream of air, thoroughly mix it to ensure even concentration and then expel the air/dust mixture out of the apparatus through a burner tube so we could ignite the mixture. Our initial design was based on the work of Mason[7].

Initial Apparatus Design

Our apparatus is based on a principal that relies more on the velocity of the air to adequately mix the dust and air. Our initial design consists of a hopper, mixing chamber, burner tube, and exhaust outlet via a vacuum pump.

This design was effective in adequately mixing the air and dust together however the orientation of the inlet tube for the dust and air into the mixing chamber created complications. When entering the mixing chamber the dust collided with the chamber wall reducing the speed and dropping some of the dust out of the air. This resulted in large piles of dust sitting at the bottom of the chamber further exacerbating the problem. The buildup of dust at the bottom of the chamber made it difficult to reach the required concentrations for combustion, requiring us to drop more dust into the airstream to try and meet the concentration requirements. This wasn't as sufficient as more dust collected at the bottom of the chamber.

In order to reduce this occurrence we decided to adjust the mixing chamber design to mitigate the buildup of dust in the chamber. A 90° elbow was added to the inlet tube directing the flow of air and dust upwards toward the burner tube. In addition a funnel was secured to the opening of the elbow spanning to the walls. In theory all the dust that didn't make it out of the chamber either through the burner tube or through the exhaust outlet would fall onto the funnel and be directed back into the air stream reticulating the dust once more. By making these alterations we anticipated to use less dust for higher concentrations allowing us to run our experiments for several minutes as opposed to a few seconds. The mixing chamber change can be seen in Figure 4.
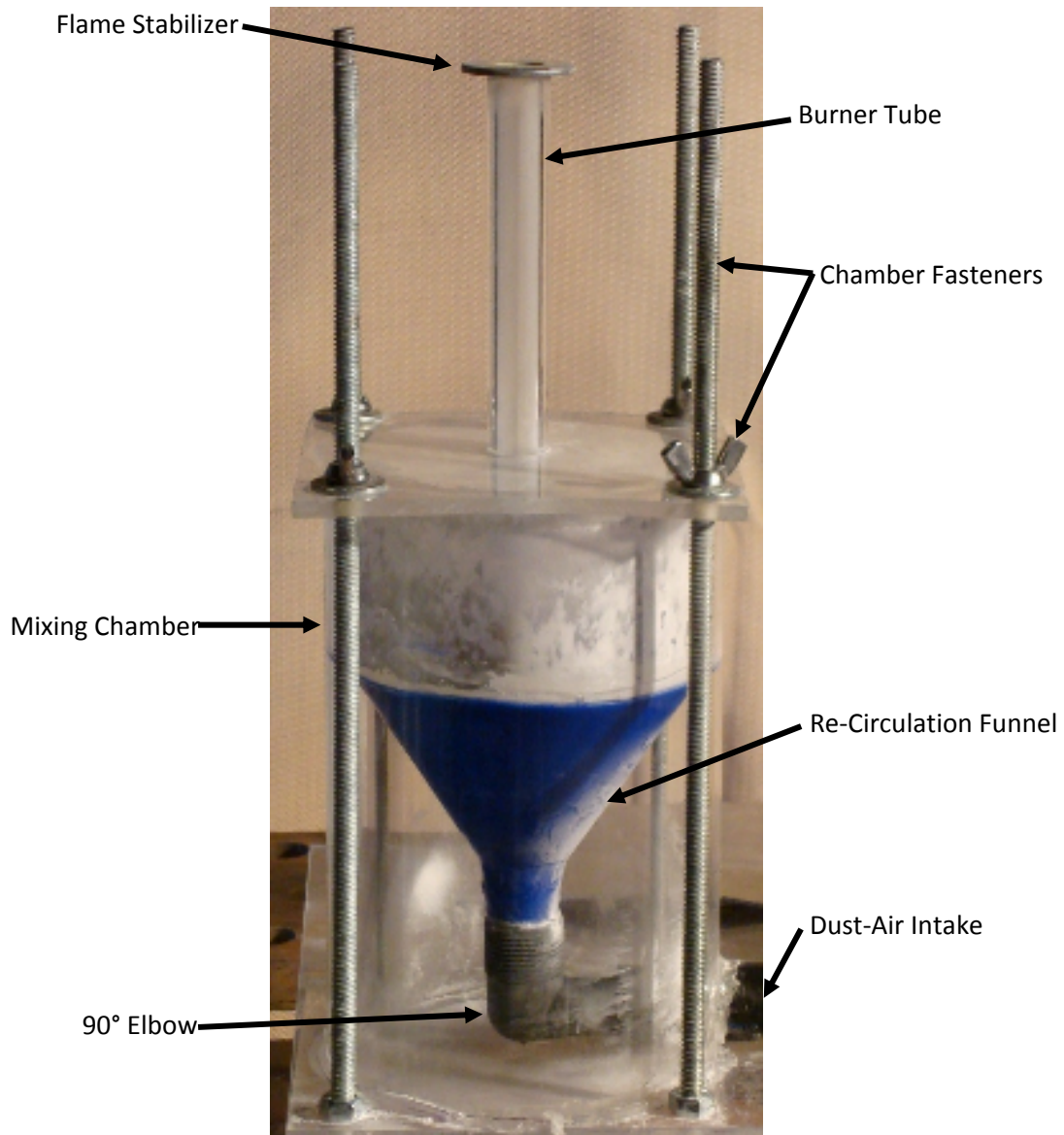
Figure 4- Mixing Chamber of apparatus where Cornstarch and air mix before leaving through the burner tube.

After installing the funnel into the mixing chamber we did encounter some issues. The plastic that was used in the funnel was statically charging the dust when it was re-circulating through the chamber resulting in the dust clumping together. The clumped dust was too large to fit through the flame arrestor mesh at the top of the burner tube and as a result the vast majority of the dust was being sucked into the vacuum. To stop this from happening, the funnel was coated to prevent the dust from coming into contact with the plastic, as a result the dust moved much more fluidly through the chamber.

Final Apparatus Design

Figure 5- Dust burner apparatus.

The final design, seen in Figure 5, consists of a motor-driven screw which consistently drops an amount of dust into the stream of air flowing though a .75 inch internal diameter CPVC pipe. The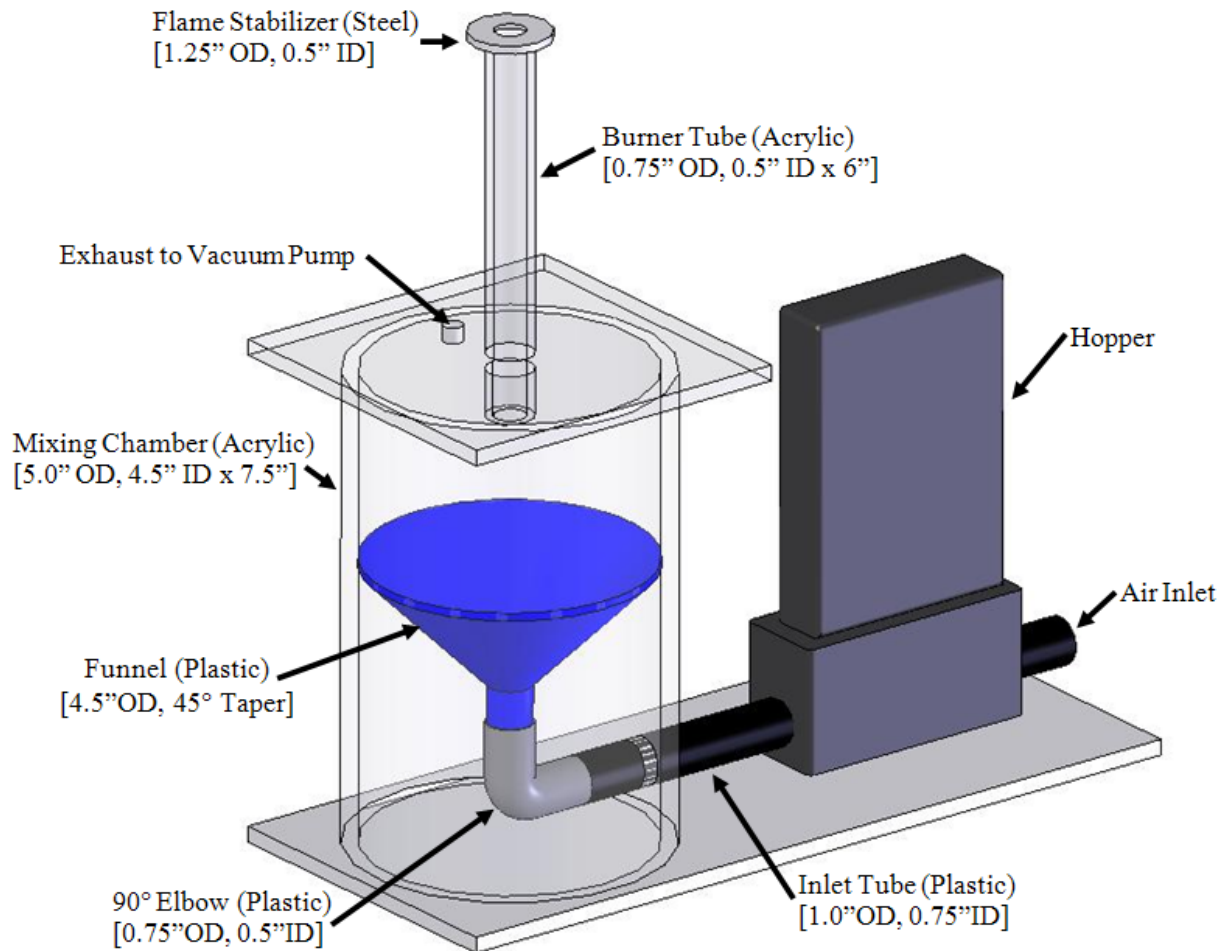 air velocity is controlled by a pressure regulator and a flow meter which were set at 60 PSI and 80 SLPM respectively. The air intake tube which has now had dust introduced into it is routed into the mixing chamber and deflected 90° upwards. The flow then passes through a funnel assembly which spans the entire mixing chamber. The mixing chamber is a 5 inch OD acrylic cylinder with 0.25 inch walls capable of withstanding high pressures. The top of the chamber is 0.25 inch plexiglass which has two holes drilled out, one for the 0.75 inch OD, 0.5 inch ID burner tube and the other for the exhaust tubing to the vacuum pump. The purpose of the vacuum pump is to remove excess air and dust flow to be able to control the exit velocity of the burner tube while still maintaining a fast, turbulent air intake. The top of the burner tube is equipped with a flat steel washer for flame stabilization and a small gauge mesh for flame arresting. Also, there is a metal plate positioned behind the burner tube to protect the vacuum pump tubing from excessive heat while flame is present. Figure 5 has a dimensioned drawing of the final apparatus.
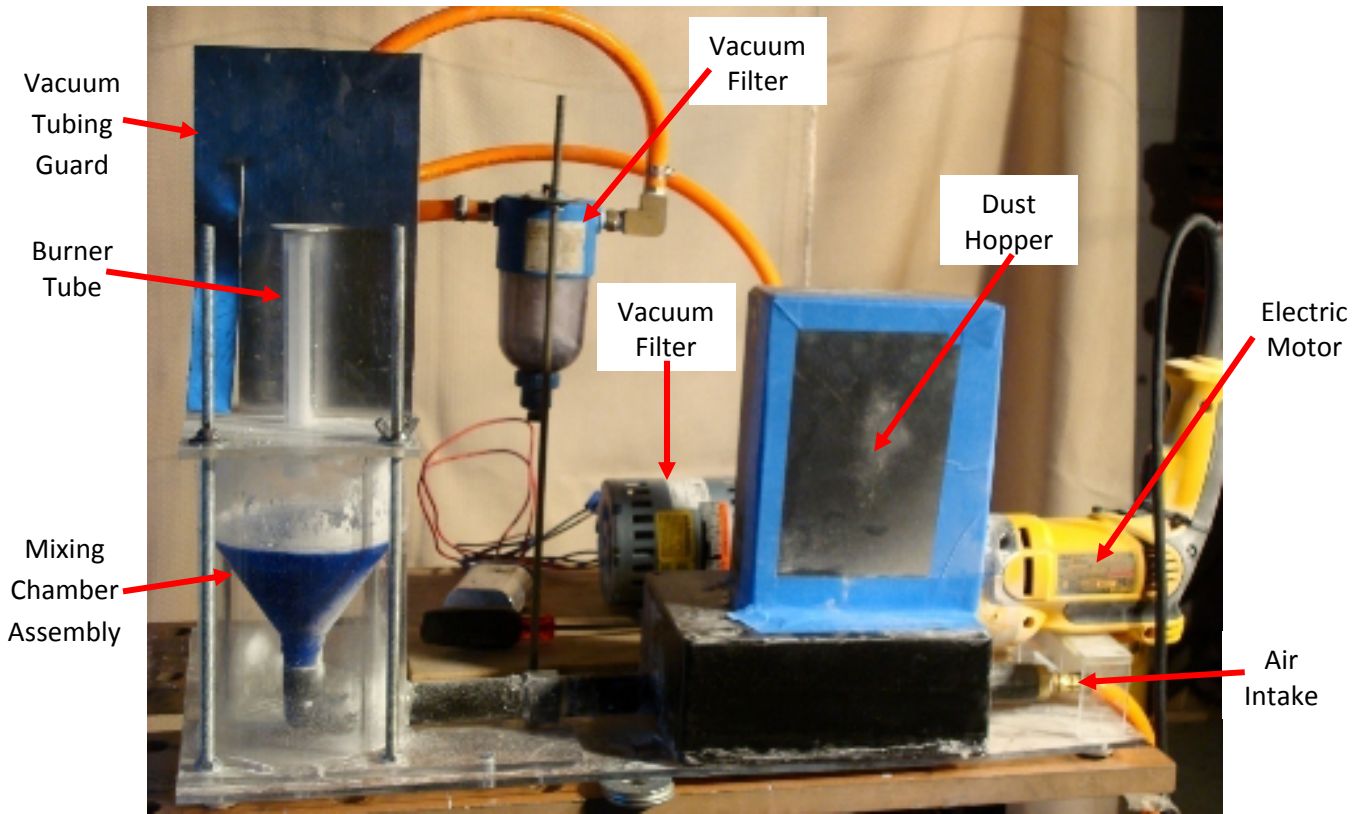
Figure 6- Final design of the Dust Apparatus.

As mentioned previously the primary dust for the combustion is cornstarch. This dust was loaded into the hopper where it would be dispersed into the air stream at a steady rate via the electric drop screw. The cornstarch was mixed with 2-3% Cabosil, a silicone based additive, which drastically increased the fluidity of the dust. This led to less clumping and an overall smoother apparatus operation compared to pure cornstarch.
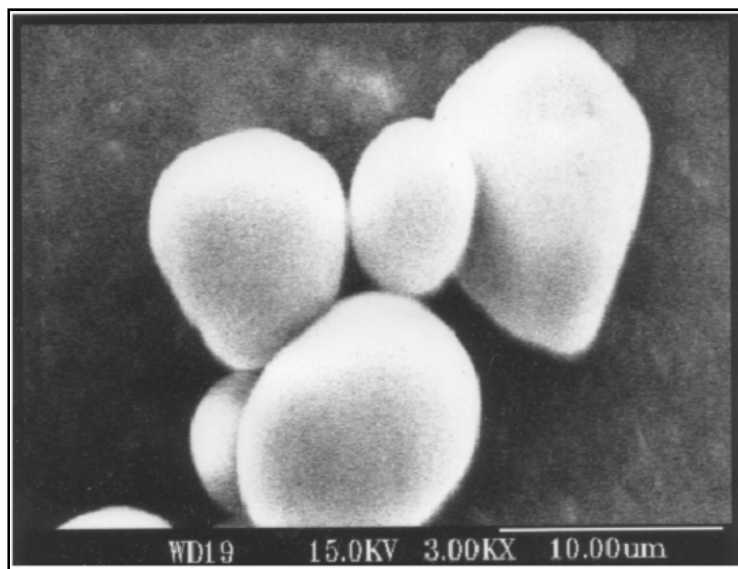
Figure 7- Microscopic Imagine of Cornstarch, Characteristic Dimension of 10µm.

Before the burning processes takes place at the final outlet of the apparatus, the concentration of the dust has to be measured to ensure that it is within the combustible region of the fuel. A coffee filter was used to collect the sample of dust in intervals of 2, 5, and 10 seconds. The mass of the filter was measured before and after the sample was taken to calculate the mass of dust collected. The velocity was measured utilizing an anemometer to determine the volumetric flow rate of the mixture, which is equal to the velocity of the mixture multiplied by the burner tube area. Concentration was then calculated based on the mass of cornstarch and the volumetric flow rate of air, taken per second. The mass of dust is then divided by the total volumetric flow rate of air to determine the concentration in g/m^3 per second. Sample calculations can be found in Appendix A.

Based on the research by Proust & Veyssiere[8] on moving flame combustion of cornstarch, the concentration of cornstarch should be between 75 and 275 g/m^3 to be combustible, although the stoichiometric combustion concentration of cornstarch is 228 g/m^3. The experimentally acquired concentration of cornstarch was in the range of 95 to 114 g/m^3 during testing, so it was determined that the mixture would be combustible.

4   Results and Discussion

In the dust burner, the main combustion reaction taking place is the combustion of cornstarch with air. Cornstarch occurs naturally as a polymer chain, where the degree of polymerization changes depending on what is used for, and can range anywhere from 100-1000 individual monomers. For the combustion reaction of cornstarch, the formula is shown as if a monomer of cornstarch reacts with air. Although the cornstarch is mixed with 2-3% Cabosil, the reaction can be ignored because it is not required for the combustion of cornstarch. When the cornstarch reaction goes to completion, only carbon dioxide (CO_2), Water (H_2O), and Nitrogen (N_2) are formed. The stoichiometric reaction is shown below:

$$C_6H_{11}O_5 + \frac{25}{4}(O_2 + 3.76N_2) \xrightarrow{yields} 6CO_2 + \frac{11}{2}H_2O + \frac{47}{2}N_2$$
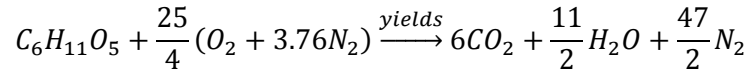
Without the reaction going to completion, many other products could be formed such as carbon monoxide, nitrous oxides, any sort of monomer from the cornstarch polymer chain, and numerous free radicals. Usually, the burnt cornstarch will cause a small amount of soot as well, which would be burnt carbon and possibly some burnt starch.

One of the correlations that we wanted to make with the project was between the laminar burning velocity and the concentration of dust. For our dust concentration measurements we proceeded to ignite the mixture and produce a laminar flame. From this laminar flame we hoped to measure either the flame angle or the flame height in order to apply either equation 2 or 3 to determine the laminar burning velocity.

There was some difficulty in getting a perfectly laminar flame in order to use equation 2, which relies on the flame angle to calculate the laminar burning velocity. These difficulties included cross flows in the fire lab as well as flame stabilization problems on the metal ring. As a result of this, equation 3, which relates the laminar burning velocity to the height and radius of the flame, was used to perform the calculation. A sample of the calculation can be found in Appendix B, and the results are shown in Figure 8.
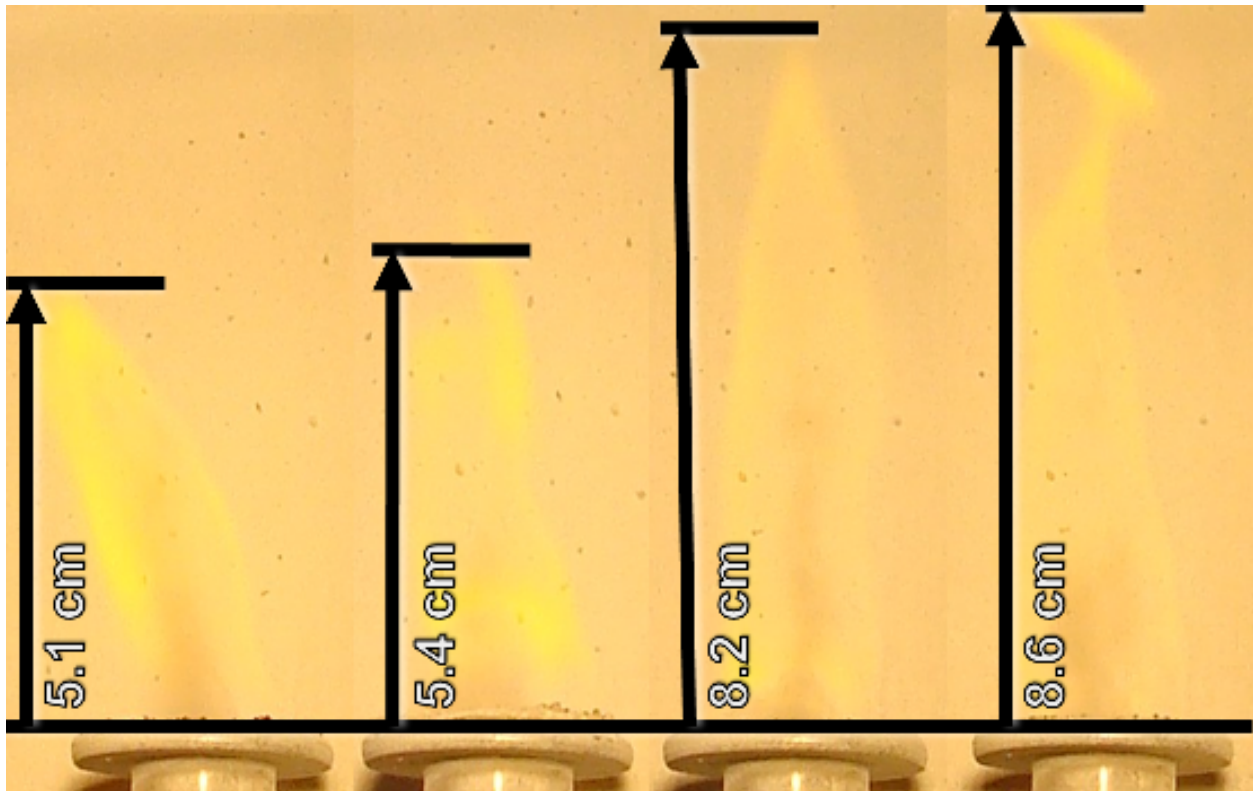
Figure 8- Height of flames based on air velocity

The height of the flame is measured from the bottom of the flame and changes based on the concentration of the dust and the velocity of the air moving out of the burner tube. The results are shown in Table 3.

Flame	Concentration [g/m^3]	Volumetric Flow Rate[m^3/s]	Flame Height [m]	Laminar Burning Velocity [m/s]
1	0.130	6.9x10^{-5}	0.051	0.135
2	0.125	7.4x10^{-5}	0.054	0.137
3	0.112	9.7x10^{-5}	0.082	0.119
4	0.116	10.6x10^{-5}	0.086	0.124

Table 2: Laminar Burning Velocity Calculations

Once the laminar burning velocity was calculated we plotted the results with the dust concentration on a graph that Dahoe[8] has previously created with his experimental data which can be seen in Figure 8. The upper curve represents parabolic flame data. A parabolic flame has a profile of a cone with a rounded top, quite literally a parabola. The lower data line represents flat flame data where the top of the flame is flat and nearly parallel to the burner tube surface.
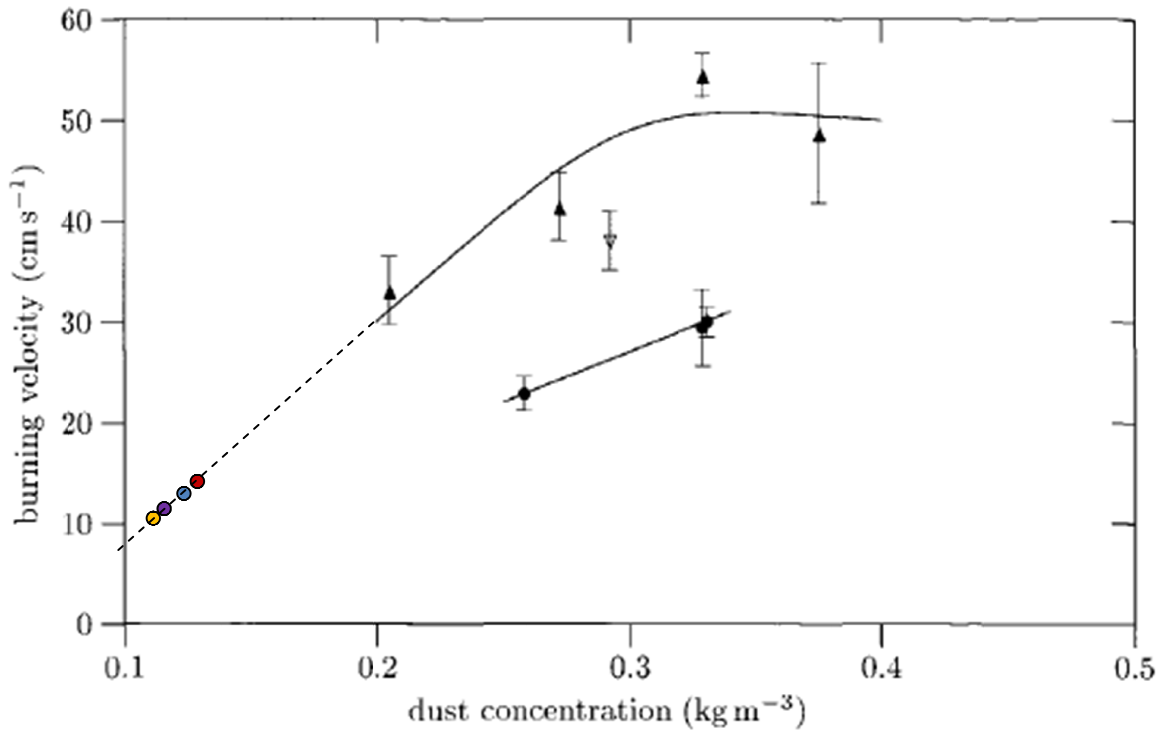
Our experimental data does not directly correlate with the study, however if the parabolic flame data was extrapolated it would intersect our results. We attribute this to two issues we faced in our experiments, concentration uncertainty and corn starch clumping. As mentioned previously we used filter paper to measure the concentration of the mixture. This inherently created issues as the dust would flow around the paper skewing our results.   Additionally we were having problems keeping a high enough concentration of dust inside the chamber. With a higher capacity vacuum pump we would have been able to have a higher velocity into the system, and theoretically a higher concentration of dust before leaving the dust burner. The higher vacuum pump would have been able to keep the velocity moving out of the burner tube at an acceptable range for combustion to occur.

To address the cornstarch clumping we used a silicone based product called Cabosil. Once mixed with the cornstarch the mixture became very fluid and we did not have any issues with the dust clumping in the apparatus. By adding the Cabosil we were adding an inert agent into the dust. Once ignited this inert agent would absorb some of the flame heat resulting in a smaller flame, thus skewing our results.

After getting a steady laminar flame out of the burner tube, the goal was to measure the concentration and the velocity of the air in order to plot our results. Once the flame was blown out, the concentration of the dust was measured while the settings of air flow rate and the hopper settings were kept constant. The air velocity was also measured using a velocity meter to determine concentration per cubic meter. Concentrations are shown in the table below and varied based on the length of test and on the precision of measurement.

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Length of Test (s)	Initial Mass (g)	Final Mass (g)	Mass of Cornstarch (g)	Concentration (g/m^3)	Velocity (cm/s)
2	1.561	1.59	0.029	144.4	56
2	1.581	1.597	0.016	49.7	127
2	1.562	1.573	0.011	77.7	56
5	1.557	1.59	0.033	41.0	127
5	1.556	1.589	0.033	93.2	56
5	1.539	1.6	0.061	96.3	84
10	1.564	1.627	0.063	49.7	127

Table 3- Measured Concentration and Velocity of Cornstarch.

The average concentration from the tests above is approximately 78.9 g/m^3. The stoichiometric concentration the dust in air mixture is about 228 g/m^3, however, our data falls within the range of what Dahoe[8] and other researchers such as Proust and Veyssiere[8] have observed and published.

Problems with Set-up

The apparatus provided several challenges during the course of the project. A significant complication was accurately and precisely changing the velocity of the airflow through the apparatus. As mentioned previously we utilized a pressure regulator as well as a flow meter to adjust the air flow. This was sufficient however even the slightest changes in the flow meter translated into large burner tube velocity changes. Additionally, towards the end of the experimentation we were noticing that the vacuum filter was clogging much quicker than in previous tests, resulting in fluctuating concentrations. This could be in part to the increased turbulence in the chamber as well as the addition of the Cabosil to the cornstarch mixture; nonetheless it was becoming an issue.

Due to the design of the apparatus we were never sure what the actual concentration or velocity of the dust mixture out of the burner tube was. These two constantly changing variables made flame stabilization quite a challenge. The velocity was a lot easier to control as it was somewhat stable and depended on the flow meter and pressure gauge positions. This alone wasn't a large contributing factor; however, the concentration of the dust in the air mixture was varied. The concentration level was tied to a speed control for the electric motor that drove the feed screw. By adjusting the speed to predetermined levels we had a good idea what the concentration was out of the burner tube. Issues arose when the dust started collecting inside the mixing chamber and the vacuum filter. As a result, the clumping of dust in the hopper or mixing chamber would directly affect the concentration coming out of the burner tube. This coupled with the unpredictable magnitude of the air velocity changes made flame stabilization challenging. For future experimentation we would recommend some slight changes to increase consistency and accuracy of data obtained from experimentation. Those changes are addressed in our conclusion.

5   Conclusion

We were able to design and develop a dust combustion apparatus as well as produce a steady flame fueled by a cornstarch-air mixture. Using this apparatus we gathered preliminary data regarding concentration, air velocity and flame dimensions. With this data we applied the laminar burning velocity equations to determine the laminar burning velocity of a cornstarch-air mixture and compared it to previous research in the field. If we had more time we would have further investigated the relationship between the concentration of cornstarch and the flame temperature as well as further studied the velocity of the flame under different concentrations and air speeds; however, the primary goal of the project was to develop a working apparatus. Grain dust explosions can be very deadly and costly and there is a lot of room for improvement for proper identification and classification of these hazards. The work we accomplished has laid a foundation for other research projects in this intriguing and somewhat unpredictable category.

6   Future Experimentation

For future experimentation we would make some minor changes to the apparatus design. We would recommend a more sensitive flow meter in order to make even smaller adjustments so that the velocity changes were more controlled. Additionally, the flow velocity instrument that we used to measure the velocity of the air exiting the burner tube did not have a high enough resolution to accurately measure the air stream. The readings were somewhat inaccurate when the numbers were in the range of 0-100 ft/s. Ideally we would have been able to use a more sensitive device to accurately gauge the air speed. We would recommend for future experimentation to have a way to reduce the flow of the dust into the vacuum either by baffles or secondary filter device. This would be a complicated task as the volumetric flow rate exiting via the vacuum is much greater than that exiting through the burner tube in order to have an air velocity that would sustain a flame. However, in the latter part of our experimentation we were still able to sustain a flame even when the vacuum filter seemed to be clogged suggesting that the revised chamber design, which incorporated a funnel to reintroduce fallen dust back into the airstream, may have been sufficient to keep the dust in the air flow, not requiring a high air velocity in the chamber. If that is in fact the case then the vacuum could be eliminated entirely, simplifying the apparatus to run at a lower air velocity with the same results. Tests must be conducted to confirm this, but it is possible.

References

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Appendix A: Sample Calculations of Cornstarch Concentration

$$Concentration = \frac{mass}{volume}$$

To determine mass of cornstarch use

$$Mass\ of\ Cornstarch = mass\ of\ filter\ after - mass\ of\ filter\ before$$

Where:

Mass of coffee filter before test: 1.561 g

Mass of coffee filter and cornstarch: 1.590 g

Mass of cornstarch: 0.029 g

To determine volume, use volumetric flow rate

$$Q = VA$$

Where:

A = area of burner tube = $\pi\ r^2$ where r = 0.00635 m

A = 0.00013 m^2

V = 1 m/s

$$Q = 1\frac{m}{s} * 0.00013m^2$$

$$Q = 0.00013\ \frac{m^3}{s}$$

This sample was taken over 2 seconds, therefore the total flow rate of air is

$$Q = 2\ s * 0.00013\ \frac{m^3}{s}$$

$$Q = 0.00025\ m^3$$

Concentration = mass / total flow rate

$$Concentration = \frac{0.029\ g}{0.00025\ m^3}$$

$$Concentration = 116\ \frac{g}{m^3}$$

Appendix B: Sample Calculation of Laminar Burning Velocity

Equation obtained from Strehlow:

$$S_u = \frac{2U}{\pi r \sqrt{l^2 + r^2}}$$

Where:
U is the volumetric flow rate, 6.9x10-5 [m3/s]
r is the radius of the burner tube, 0.00634 [m]
l is the height of the flame, 0.051 [m]

$$S_u = \frac{2\left(6.9E^{-5}\left[\frac{m^3}{s}\right]\right)}{\pi(0.00634\ [m])\sqrt{(0.051\ [m])^2 + (0.00634\ [m])^2}}$$

$$= \frac{13.8E^{-5}\ \left[\frac{m^3}{s}\right]}{\pi(0.00634\ [m])\sqrt{0.002641\ [m^2]}}$$

$$= 13.5\ \left[\frac{m}{s}\right]$$

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Advising Professors: A. S. Rangwala (FPE) & N. K. Kazantzis (ChE)

INTRODUCTION

Worldwide, various industries use a diverse range of dust types. Depending on the process needs of the industry, theses dusts are stored, creating large stockpiles in large silos or compartments. The types of dust range from agricultural, such as cornstarch, to fuel, like coal. In order to make a standard of how to protect facilities from large and dangerous dust explosions, the NFPA utilizes a system of explosion hazard classification that relies on a deflagration index. As part of this project, the goal was to find more measureable explosion characteristics that could be used for hazard classification. This study investigates the laminar burning velocity based on the concentration of a cornstarch and air dust mixture. Throughout the project the group designed and developed a dust combustion apparatus and utilized this apparatus to burn the dust at various concentrations and velocities to record the flame angle and area. The research obtained could be used to mitigate the fire explosion risk in grain silos and similar storage containers.
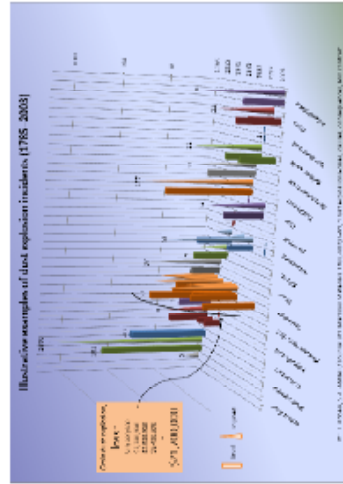
Figure 1. Illustrative Examples of Dust Explosions (1785-2003) (Source: Venet)

CHARACTERISTIC EQUATIONS

When cornstarch goes through the combustion reaction with air, the main products of the reaction are Carbon Dioxide (CO_2), Water (H_2O), and Nitrogen (N_2) as shown below:

$$C_6H_{11}O_5 + \frac{25}{4}(O_2 + 3.76N_2) \xrightarrow{yields} 6CO_2 + \frac{11}{2}H_2O + \frac{47}{2}N_2$$

In order to calculate the laminar burning velocity of the flame, the following equations can be used. If the flame angle can be measured easily, the equation is simple and relates the velocity out of the burner tube to the angle:

$$S_u = U \sin \alpha$$

If the flame angle cannot be easily measured, the radius, height, and volumetric flow rate of the fire can be used to determine the laminar burning velocity,

$$S_u = \frac{2V}{\pi r \sqrt{h^2 + r^2}}$$

S_u = Laminar burning velocity [m/s] V = Volumetric flow rate [m³/s]
U = Exit velocity [m/s] h = height of flame [m]
α = flame angle [degree] r = radius of flame [m]

EXPERIMENTAL SETUP

The most important component of our research was the apparatus. Our apparatus needed to consistently add the cornstarch into a stream of air, thoroughly mix it to ensure even concentration and then expel the air-dust mixture out of the apparatus through a burner tube so we could ignite the mixture.
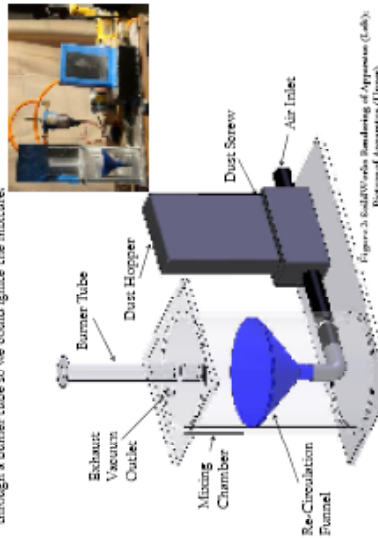
Figure 2: Solidworks Rendering of Apparatus (Left)
Pictured Apparatus (Upper)

Air enters the apparatus through the inlet tube on the left. The air flows through the bottom of the hopper where an electric motor driven screw drops a set amount of dust into the airstream. From there the air and cornstarch dust mixture is sent into the mixing chamber. In the mixing chamber it exits either through the burner tube or through the exhaust vacuum port. The chamber is outfitted with a funnel to promote the recirculation of any dust which may have fallen from the airstream. The mixture that exits through the burner tube is ignited and flame measurements are taken.

CONCENTRATION MEASUREMENTS

As part of the data acquisition we calculated the concentration of dust required to obtain a flame. To do this we utilized a conical filter paper and held it over the stream of dust coming out of the burner tube. The mass of the paper was measured before and after the duration of the test. The mass measurement, coupled with the burner velocity and the volumetric flow rate allowed us to calculate the concentration of dust exiting the burner tube. The results are as follows:

Length of Test [seconds]	Initial Mass [grams]	Final Mass [grams]	Mass of Cornstarch [grams]	Concentration [grams/meter³]
2	1.561	1.590	0.029	144.4
2	1.581	1.597	0.016	49.7
2	1.562	1.573	0.011	77.7
5	1.557	1.590	0.033	4.0
5	1.556	1.589	0.033	93.2
5	1.539	1.600	0.061	96.3
10	1.564	1.627	0.063	49.7

FLAME MEASUREMENTS

Once a flame was stabilized on the burner tube we measured the height of the flame to apply it to the equations in order to determine the burning velocity of the cornstarch dust mixture.
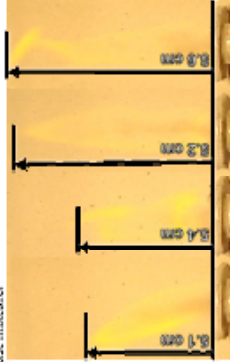
Figure 3: Experimental Flame Measurements

Utilizing the characteristic equations and the measured flame heights we found the burning velocity to be 13.5, 13.7, 11.9 and 12.4 [cm/s] respectively. These values do roughly correlate to the value curve derived by Dahoe in Figure 4.
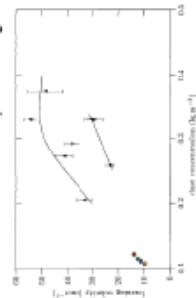
Figure 4. The Laminar Burning Velocity, S_u, (Source: Dahoe)

CONCLUSIONS

At the conclusion of the project we were able to design and develop a dust combustion apparatus as well as produce a steady flame fueled by a cornstarch-air mixture. Naturally, due some of the complexities of the project, we were not able to accomplish everything in the depth that we would have liked to. If we had more time we would have further investigated the relationship between the concentration of cornstarch and the flame temperature as well as the velocity of the flame under different circumstances.

Grain dust explosions can be very deadly and costly and there is a lot of room for improvement for proper identification and classification of these hazards. The work we accomplished has laid a foundation for other research projects in this intriguing and somewhat unpredictable category.

REFERENCES
Dahoe, A. E. (2000). Dust Explosions: A study of Flame Propagation. Netherlands, pp 229.
Streslow, R. A. (1984). Combustion fundamentals. New York: McGraw-Hill. pp 235-260.
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Fire Science Laboratory
Short Form for Short Tests

The purpose of this form is to provide a simple way for students to develop an Experimental Plan for short, uncomplicated tests rather than using the Experimental Plan Template. The numbers listed below match the steps in How to Develop an Experimental Plan. You should read that first to learn how to develop a plan and then use the following format to present it.

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1. Background
   Reason for doing experiment:

   Produce flame from combusting mixture of cornstarch and air. Measure heigth and possibly flame angle of the flame, depending on results of flame.
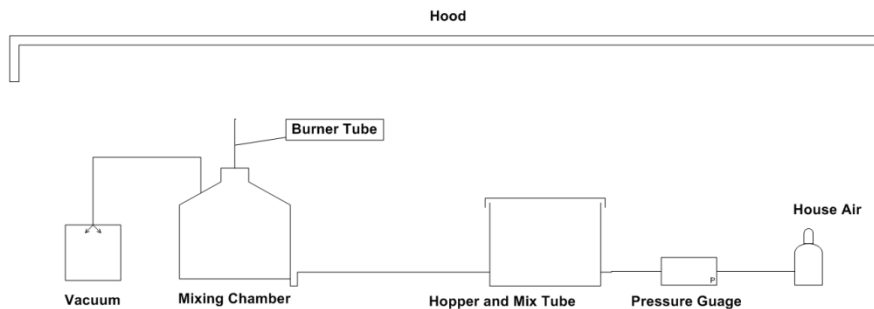
2. Objective
   Data/information you trying to obtain:

   Data collection will include finding the velocity of the air exiting the burner tube of the apparatus, and measuring concentration through timed dust collection through a coffee filter.

3. Process flow and instrumentation diagram (PID)
   Draw your PID:

4. PID components

List components of PID:

- Hopper
- Air Compressor
- Mix Tube
- Mixing Chamber
- Vacuum
- Burner Tube
- Ventilation Hood

5. Safety issues
List materials and chemicals to be used, required use and hazards:

Flammable mixture of cornstarch and air will be used throughout the experiment. A lighter will also be used to start the combustion process once the fuel and air are flowing through the apparatus. One of the safety issues presented is an uncontrolled combustion due to how much fuel is used or available for combustion. The chamber measures about 4000 cubic centimeters (or 0.004 cubic meters) and a way to control the uncontrolled combustion in this chamber would be to have a flame control in the design to prevent the combustion from getting out of hand. The MSDS for each chemical can be found on file in the Fire Lab.

List Protective Personal Equipment to be worn to protect against those hazards:

Goggles will be used to protect eyes from heat and possible dust particles which do not react completely in the combustion. Fire gloves will be used to deal with hot or warm equipment to prevent burns, and a dust mask may be used if there is a larger amount of dust in the atmosphere than expected.

6. Failure possibilities
List failure possibilities of EACH of the PID components and how you will minimize these:

(1) Hopper: Should the hopper fail in that it fails to drop cornstarch into the air stream there would be no potentially hazardous effects as that all that would be leaving the burner tube would be air. If too much dust is released into the air stream, the flame could burn faster or hotter, but there would not be a problem until the concentration exceeded the upper flammability limit. In order to minimize these failure possibilities, is to periodically check the concentration of dust in the system, if it should drastically change in a short period of time, something has most likely gone wrong and the test should be safely shutdown.

(2) Air Compressor: Should the air compressor fail, the stream of air in the system would be reduced to zero. This could be a hazardous situation in that the vacuum pump, which would still be running, could possibly suck the flame into the mixing chamber where if there was sufficient oxygen the chamber, the mixture could cause uncontrolled combustion. Also the flow of the air must be closely watched to ensure that there is sufficient flow to allow for laminar combustion, too much or too little flow could result in hazardous conditions and possible uncontrolled combustion either in the chamber or atmosphere. To control this hazard, a pressure gauge will show a change in pressure in the chamber if the house air were to fail or get clogged. Another way to determine if the air compressor has failed is if it stops making noise.

(3) Mix Tube: Should the mixture tube fail there could be a stream of air/fuel mixture streaming into the atmosphere which could be a potentially explosive situation should the mixture reach an ignition source. Before or during tests, the system could be checked with just air to make sure there are no major leaks anyway. If a leak exists, the tubing would have to be replaced or repaired to prevent further damage or hazardous situations.

(4) Mixing Chamber: Similar to the mixture tube, should the mixing chamber fail the result could be a leak of air/fuel in the atmosphere, which if that reached an ignition source could result in a potentially explosive situation. The pressure gauge will show if there is a problem with a leak in the mixing chamber, assuming single failure scenario, same as the air check.

(5) Vacuum: If the vacuum pump should fail, the velocity of the mixture leaving the burner tube would increase most likely resulting in the extinguishment if the flame. However, the mixture could eventually reach a flammable concentration in the atmosphere and combust if it met an ignition source. If the vacuum pump is removing too much air from the system, there may not be a high enough flow rate of air out of the burner tube to sustain a flame. Same minimization procedures as before.

(6) Burner Tube: We do not foresee any hazardous situations if the burner tube should fail.

(7) Ventilation Hood: Should the ventilation hood fail or be improperly operated there is the risk of building up a concentration of dust in the room which could lead to an explosion.

Overall, a leak anywhere in the system could prevent a hazardous situation and lead to uncontrolled combustion. This could also cause the pressure in the mixing chamber to change either extinguishing the flame, or pulling the flame backwards into the mixing chamber.

7. Checklist
   Write a checklist which encompasses all your procedures: Include pre-test, test and post-test activities Use additional/separate sheet if needed:

   - Before test begins:
     - Turn on vent hood

- Weight dust
- Instrument check
- Safety review
- Test procedure:
  - Ensure PPE is worn properly where necessary
  - Insert dust into hopper
  - Turn on air and ensure flow rate is correct, and check for any possibly leaks in the entire system
  - Begin seeding the dust into the chamber using variable speed of the hopper depending on what concentration of dust in air is needed and the speed of the air in the chamber
  - Once hopper and air streams reach steady state, an electric match or propane torch can be used to start the flame at the top of the burner tube
  - Collect data to ensure the system is working properly, and to get data for results. Pressure should stay positive in the chamber to ensure that the flame does not get sucked back into the chamber and cause a larger, uncontrolled explosion. The adiabatic flame temperature will be measured for results, flow rate of dust and air will be known, and the concentration will be measured once the system is calibrated.
- Post Test:
  - Clean up procedure, including making sure dust is not on the floor, equipment is not in anyone's way and tools are returned to their place
  - Check data
  - Turn off dust hopper
  - Leave HVAC on if needed, or turn off if ventilation has been sufficient

8. Checklist specifics
   Plan to inform others of activities:

   Inform lab manager and others in the lab about the test occurring

   Number of people needed to run: 2

9. Emergency shutdown
   List events that necessitate an immediate shutdown:

   - General Building Alarm
   - Uncontrolled Combustion
   - Loose hose or leaks in the system
   - Lose electric power in the room, or building, which would cause the hood to stop working

10. & 11. Apparatus checkout
    How will you know if all the components work properly?

The instruments should have regular readings such as expected concentrations and velocity measurements.

12. Team review
Explain how all team members will know what is going on:

Specific jobs will be given to each team member based on what kind of test is being performed and what kind of data is necessary for the test. Another important aspect of running the tests and understanding who should complete what tasks is to complete a safety review before any test begins.

13. & 14. Pre-test and test
Explain how you will know the information obtained is valid (i.e., reasonable or makes sense):

Pre-test information should be clear, there should be little to no dust or air escaping from the system. The test information will be validated based on sustaining a flame and ensuring that the flame does not back up into the combustion chamber. Also, without the proper mixture of cornstarch and air, no combustion will occur, showing that the test was not valid.

15. Post-test
List what/how you will clean post-test:

To clean up post-test, the lab group will make sure the area looks similar to how the area looked before the test began, if not cleaner. Tools will be replaced and excess dust will be removed from the area. The hood will be evaluated on a case by case basis to determine if it needs to be left on for an extended period of time.