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Evaluation of the 20 L dust explosibility testing chamber and comparison to a modified 38 L vessel for underground coal

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ABSTRACT

The phenomenon of combustible dust explosions is present within many industries. Tests for explosibility of dust clouds per ASTM E1226 use a 20 L explosive chamber that places the combustible dust directly below the dispersion nozzle which generates a thorough mixture for testing purposes. However, in the underground coal mining industry, there are a number of geologic, mining, and regulatory factors that change the deposition scheme of combustible coal dust. This causes the atmosphere of a coal mine to have a variable rock dust-coal dust mixture at the time of ignition. To investigate the impact of this variable atmosphere, a series of lean explosibility tests were conducted on a sample of Pittsburgh Pulverized coal dust. These explosibility tests were conducted in a 38 L chamber with a 5 kJ Sobbe igniter. The 38 L chamber generates a variable air-dust mixture prior to ignition. The test results indicate that the 38 L chamber experiences reduced explosive pressures, and lower explosibility index values when compared to the 20 L chamber.

1. Introduction

Coal dust explosions in underground coal mines are among the deadliest mining disasters. The Mine Health and Safety Administration (MSHA) classifies any mining accident that claims 5 or more lives as a mining disaster [1]. Since 1970, 21 coal mine disasters have occurred in the United States. 15 of these have been categorized as explosions, this accounts for 71% of all coal mine disasters. These explosions have accounted for 201, or 77% of all disaster fatalities occurring during this period [1]. Mitigation and prevention of coal dust explosions has been widely researched with decades of worldwide research [2]. However, the phenomenon of combustible dust explosions is not unique to the coal mining industry. Many types of combustible dusts are generated, processed, handled and stored in industrial facilities. When ignited, these dusts can burn rapidly and can generate considerable explosive force in the proper conditions [3].

To properly prevent a dust explosion from occurring, it is necessary to understand the atmospheric conditions that must be present for an explosion to occur and propagate. Standardized tests have been developed through research to investigate the explosive conditions of combustible dusts. These tests simulate a dust explosion within an explosive chamber of known volume. Using the overpressure ratio and the rate of pressure rise, the explosion can be categorized.

2. Background

The first test apparatus developed by the United States Bureau of Mines (USBM) was approximately 8 L in volume and based upon the Hartmann chamber, previously developed by the bureau for explosibility studies of homogenous gas mixtures [4]. Results from these tests were reported in terms of nominal concentrations where a direct calculation was made between the mass of dust divided by the chamber volume. This chamber did not allow for thorough mixing of the dust prior to ignition. An optical probe was used inside the chamber to measure the concentration of dust at specific points. The primary concern with the modified Hartmann chamber was that the realized ignition energy was limited due to the small volume [4].

A 20 L spherical chamber designed by Siwekwhich was designed for thorough mixing of the combustible dust particles prior to ignition [5]. This was achieved by placing the dust reservoir in the path of the dispersion air. When the pressurized air was injected into the chamber, the dust reservoir would be emptied in the process, allowing for a thorough mixture. This chamber is comparable to the Bartknecht 1 m^3 standard test chamber used in Europe [6]. When using the Bartknecht chamber, explosive dust

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samples are placed into a 5.4 L dust container that is attached to the chamber. The dust is dispersed into the chamber using a semi-annular, perforated half-ring with 13 holes of 6-mm diameter. After a determined ignition delay time, the dust cloud is ignited by a 10 kJ igniter [6].

A 20 L volume explosive chamber was adopted by the USBM as the standard apparatus for dust explosibility testing. Cashdollar and Hertzberg conducted a test series using an explosive chamber that was constructed of 304 steel with a pressure rating of 2100 kPa [7]. The coal dust was placed in a reservoir at the bottom of the dust chamber. Pressurized air injected into the chamber dispersed the dust from the nozzle. This design ensures that the dust reservoir will be emptied, which will result in a thorough air-dust mixture before ignition of the chamber. Optical dust probes monitored the dust dispersion within the chamber. A schematic of the 20 L chamber used by the USBM is shown in Fig. 1. The results of the testing in this chamber were reported in terms of the overpressure ratio and the rate of pressure rise.

Overpressure ratio is defined as the maximum explosive pressure achieved divided by the pressure at the ignition point of the explosion. Standard testing procedures are designed for an ignition pressure of 101 kPa, in which case the overpressure ratio is simply expressed as the maximum explosive pressure. The rate of pressure rise is simply defined as the derivative of the pressure function with respect to time. Furthermore, the pressure derivative can be volume-normalized to allow for direct comparison of explosive chambers with different volumes. Using these two criteria, the USBM established two standards for significant flame propagation: (1) the pressure ratio greater than 200 kPa, and (2) the cubic root of the volume-normalized pressure time derivative greater than 150 kPa m/s [8]. Significant flame propagation is defined as the minimum propagation required to cause serious damage to personnel and equipment in the mine [8].

Combustible dust explosions are not unique to the coal mining industry. Industries such as agriculture, chemicals, pharmaceuticals, and metal processing are also at risk of a combustible dust explosion [9]. Similarly to the coal mining industry, there is an extensive body of research conducted to mitigate and minimize the risk of a dust explosion in these industries. The results of tests conducted in this chamber can be recorded in terms of the overpressure ratio and the rate of pressure rise. One of the chambers commonly used in this testing is the KSEP-20 type explosive chamber [3]. The design of this chamber is identical to the original Siwek 20 L chamber. Standardized tests include the use of a 20 L explosive chamber which uses pressurized air to disperse and create a thorough mixture by placing the combustible dust reservoir before the dispersion nozzle. This ensures that the dust reservoir will be emptied before ignition occurs, which will result in a thorough mixture of combustible dust and air.

Table 1
Classification of the combustible dust explosion according to explosion index K_{st} [1,3].

Dust explosion index	K_{st} (kPa m/s)	Characteristic
St 0	0	No explosion
St 1	0–20.000	Weak explosion
St 2	20.000–30.000	Strong explosion
St 3	>30.000	Very strong explosion

Using the data obtained from testing in an explosive chamber, a parameter (K_{st}) specific to each combustible dust and test series can be calculated according to the cubic law (Eq. (1)). A classification scheme was developed based upon the K_{st} index. This classification scheme is shown in Table 1. In a series of tests conducted on a given combustible dust, the maximum $\left(\frac{dP}{dt}\right)$ value is used (resulting in the highest K_{st}) to evaluate the dust explosion index. If multiple series of tests are conducted on the same combustible dust, the average of the maximum $\left(\frac{dP}{dt}\right)$ values are used to calculate the dust explosion index [1,3].

$$K_{st} = \left(\frac{dP}{dt}\right)V^{1/3} \quad (1)$$

The formulation of the K_{st} index is based upon the assumption of a thorough air-dust mixture prior to the ignition of the test sample. This is common of the aforementioned industries, where inerting agents/dusts are not added to the atmosphere to mitigate the propagation of an explosion. This is not the case for the coal industry, where rock dusting is a mandatory practice.

Rock dusting is the practice of applying pulverized, inert rock (primarily limestone) to the roof, ribs, and floor of all areas of the mine [10]. During the active mining process, float coal dust is continuously generated and carried by ventilation currents throughout areas of the mine until it is deposited on top of the rock dust layer. Periodically, a new layer of rock dust is deposited on top of the float coal dust layer to prevent the entrainment of the float dust in the event of an explosion. This cycle results in a situation in which there are multiple dust beds that are distinctly layered [11].

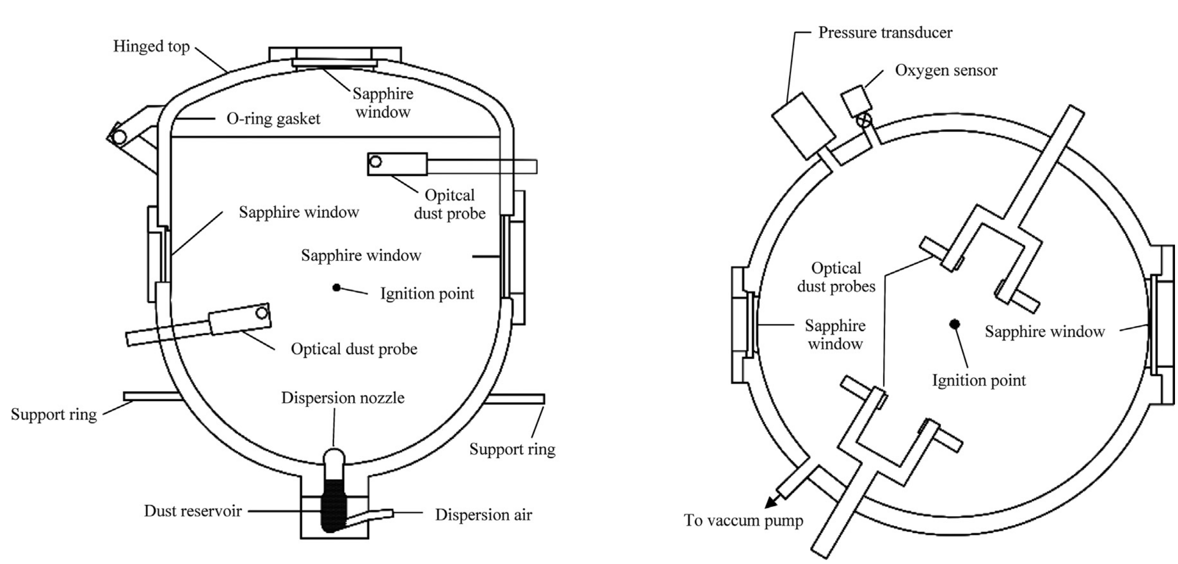

Fig. 1. Vertical (left) and horizontal (right) cross sections of the 20 L explosibility chamber adapted from [7].

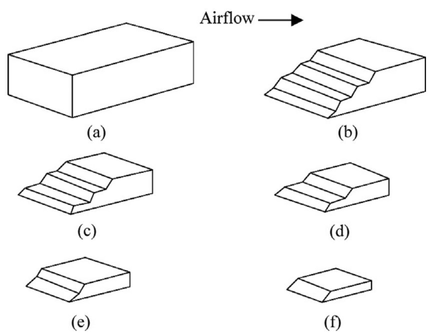

Fig. 2. Diagrammatic model of successive stages of layered-type dust beds, adapted from [11].

A coal dust explosion requires two basic conditions: the rise of a coal dust cloud in the heading and ignition of the dust cloud [12].

In a study conducted by Singer and colleagues, there are two major dispersal modes that occur simultaneously during explosion-induced airflows: lifting of top layers from along the entire bed length (surface source entrainment), and longitudinal regression of the stepped leading surface facing the air-flow (line source entrainment) [11].

During this process, dust bed dimensions are reduced continuously in the vertical and forward directions. A diagrammatic model of these dispersal modes is shown in Fig. 2. For thin dust beds the second dispersal mode is dominant, but as the thickness of the beds increases, both modes of dispersal are equally important. Due to these dispersal modes, the mine atmosphere will be variably mixed based upon the variable bed dimensions during a coal dust explosion. However, all standardized tests require that the air-dust mixture be thoroughly mixed prior to ignition [13].

As noted in Fig. 2, Fig. 2a shows the undisturbed dust beds, while Fig. 2b–f show the continuous dispersion of dust beds through time due to constant airflow.

It is important to note that while rock dusting is mentioned throughout this paper, rock dust was not used in the research presented in this paper. However, it is necessary to understand that the presence of the inert rock dust within an underground coal mine creates a unique situation when compared to other industries where a combustible dust explosion is possible. In an underground coal mine, the atmosphere will be composed of both combustible float coal dust and inert rock dust particles in the event of an explosion. This will create non-uniform mixtures that will vary throughout the mine. This is not the case when compared to other industries such as: agriculture, chemicals, and pharmaceuticals.

3. Sample preparation

A sample of Pittsburgh Pulverized was shipped to the university, and a sieve analysis was conducted on the sample to determine the particle size distribution. The results of this sieve analysis are shown in Table 2, and graphically displayed in Fig. 3.

Table 2
Sieve analysis for Pittsburgh Pulverized sample.

Sieve	Sieve Size (μm)	Retained (%)	Cumulative retained (%)	Cumulative passing (%)
8	2360	0	0	100
16	1180	0	0	100
30	600	0	0	100
50	300	4	4	96
100	150	27	30	70
200	75	31	61	39
325	45	15	76	24
325+	45-	24	100	0

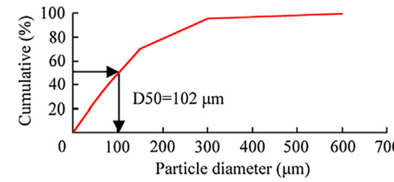

Fig. 3. Particle size analysis for Pittsburgh Pulverized sample.

The results of the sieve analysis showed that the D50 for the sample that was used in the explosibility test series was 102 μm. The coal dust sample received by the research team had no additional preparation, and was tested as received from the supplier. This was done to simulate the float coal dust that is only exposed to the temperature and humidity conditions of an underground coal mine for a relatively short period of time before rock dust is re-applied to the entry.

4. Experimental apparatus and testing procedure

Coal dust explosion trials were conducted using a 38 L chamber as shown in Fig. 4. This chamber is modeled after the Siwek 20 L chamber. The chamber was tested prior to use by Materials Engineering and Testing Corporation and approved to accept pressures up to 2068 kPa [14]. A schematic of the 38 L chamber is shown in Fig. 5. This chamber was used in a series of tests evaluating the performance of new rock dusting technologies to industry-standard technologies [10]. The chamber has a length of 61 cm, and a diameter of 30.5 cm. The L/D ratio for this vessel is therefore two, which is different than the standard test vessel used in these tests, which has a ratio of one. The 38 L chamber was designed with these dimensions to simulate the conditions of an underground coal mine. This design allows the sample to be place in front of the dispersion nozzle so that the air will pass over the coal dust, instead of underneath the sample as in the 20 L chamber design.

The pressure sensor used for the 38 L chamber was the Omegadyne PX-409. This piezoelectric sensor outputs a voltage between 0–10 V, which can be converted to a pressure reading between

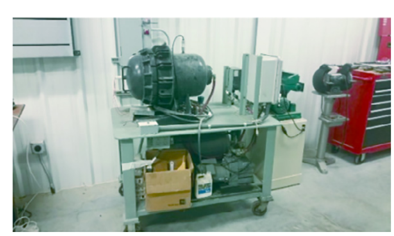

Fig. 4. Explosive chamber used in flame extinguishing experiment.

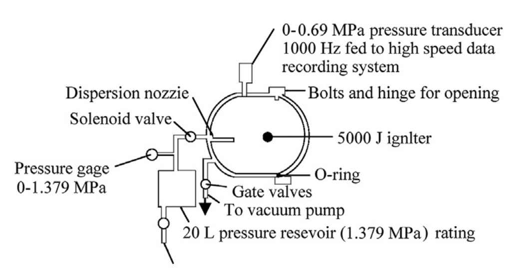

Fig. 5. Cross-section view of the 38 L explosibility chamber, adapted from [14].

Fig. 6. Omegadyne PX409 pressure sensor installed on 38 L chamber.

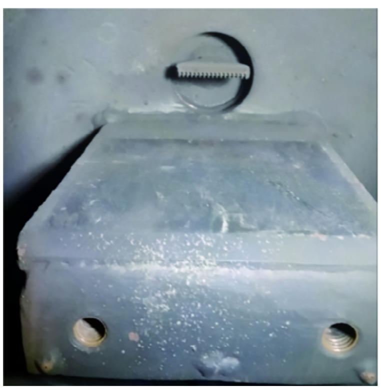

Fig. 7. WindJet AA727-1/4-SS-15 air nozzle installed in 38 L chamber.

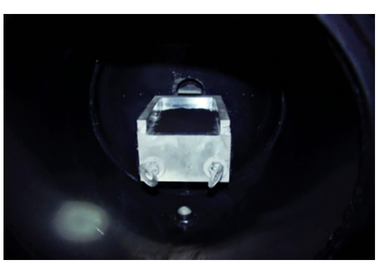

Fig. 8. Sample tray installed in explosive chamber loaded with coal dust.

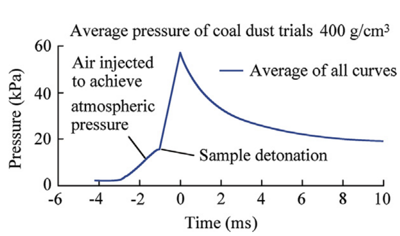

Fig. 9. Average recorded pressure within explosion chamber during coal dust experimental trials.

0–1.72 MPa. This sensor was selected due to its high standard measuring accuracy, and is placed directly above the coal dust sample. Fig. 6 shows the pressure sensor used in this test series installed at the top of the 38 L chamber. The nozzle used for air dispersion was the WindJet AA727-1/4-SS-15. This nozzle was selected for its ability to generate a controlled air pattern for uniform distribution, and ability to withstand high temperatures. Fig. 7 shows the WindJet nozzle installed in the back of the 38 L chamber.

A design alteration to the chamber is that a tray containing the test sample is installed into middle of the chamber. This is a significant change to the design of the explosive chamber because the air is injected into the chamber before coming into contact with the coal dust. The pressurized air is blown from the back of the chamber directly over top of the sample. This was done to simulate typical float dust conditions in an underground coal mine. Due to this configuration, the air-dust mixture is not thoroughly mixed prior to ignition, which simulates the layered-type dust beds that are more representative of the situation for coal mines. A typical sample inserted into the 38 L chamber prior to dispersal from the pressurized air is shown in Fig. 8.

Once the sample was installed into the chamber, the chamber was sealed. A vacuum pump was then activated and the chamber was drawn down to a pressure of approximately 13.8 kPa; during that time, a pressure reservoir used to blow air over the top of the sample to provide lift was filled to 965 kPa. The pressure reservoir was filled to approximately 965 kPa to ensure dispersion of the dust sample to recreate a typical float dust mine atmosphere, prior to a dust explosion, and to allow for comparison between previously published data, and the results of this research [8]. A vacuum was necessary so that the air injected into the chamber for the purpose of dust dispersion would bring the internal chamber pressure back up to atmospheric pressure (101 kPa) at which time the igniter fired. If a vacuum was not created, the internal chamber pressure would exceed atmospheric pressure at the time of ignition due to the injected dispersion air in the sealed chamber.

A software package developed in LabView was used to control the various processes in the experiment. The interior pressure was constantly monitored using this software package, and the blower was shut off and the igniter was detonated when atmospheric pressure, (approximately 101 kPa) was achieved [10]. Through the use of this software the delay time between the shut off of the blower and the ignition of the detonator is constant between each trial. The average pressure measured within the chamber is shown in Fig. 9. Based on the recorded pressure in the chamber, it is clear when the air was injected into the chamber to disperse the dust and bring the inside pressure back to atmospheric, and when the valve was closed, and the detonation occurred.

5. Results and comparisons

A series of coal dust explosion tests was conducted using the 20 L Siwek chamber by the USBM using coal dust from the Pittsburgh coal seam. The tests were designed to measure the lean explosibility limit of pure coal dust by measuring the bureau's criteria for significant flame propagation. The ignition pressure for all tests was conducted at 101 kPa, and therefore the pressure ratio (bar/bar) is simplified to the peak pressure. A moderate level of air turbulence was used to simulate the standard air flow conditions of an underground coal mine [7]. The results are shown in Fig. 10.

Similarly, a series of lean explosibility tests was conducted using the 38 L chamber. This test series utilized Pittsburgh Pulverized coal dust. In total, eight different masses of coal dust were tested. In total, 24 total trials were conducted with coal dust alone. These tests used increments of 7.6 g of coal dust. When normalized to the 38 L chamber, this results in concentration increments of 200 g/m^3. The results of this test series are shown in Fig. 11. Trials were conducted at 100 g/m^3 to investigate the effects of very small concentrations within the explosive chamber. A 4th trial was conducted at 1200 g/m^3 because there was a wide variation in the

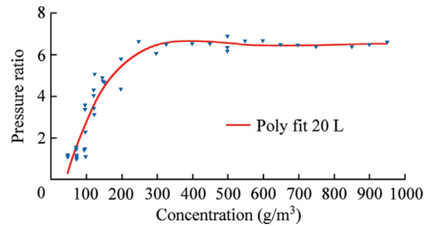

Fig. 10. Pressure ratio data for Pittsburgh seam bituminous coal dust in air at a moderate turbulence level adapted from [7].

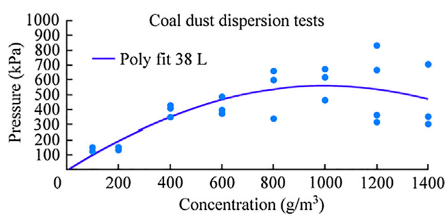

Fig. 11. Coal dust dispersion tests using 38 L explosive chamber adapted from [10].

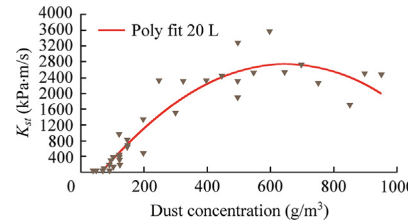

Fig. 13. K_{st} data for Pittsburgh seam bituminous coal dust in air at a moderate turbulence level adapted from [7].

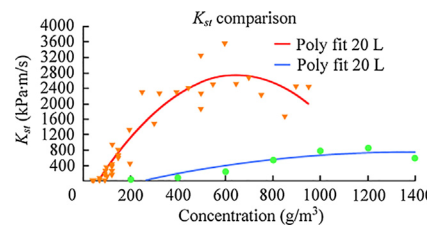

Fig. 14. K_{st} comparison between 20 and 38 L chamber.

peak pressure that was recorded between the trials. The pressure values used to disperse the coal dust into the chamber remained constant at 1034 kPa, this was done to ensure that the air was injected at the required 965 kPa.

After inspecting the data, it is evident that as the concentration of coal dust increases, there is an upward trend in the maximum explosive pressure. However, there is also increasing variability between the trials. This variation can be explained by the incomplete air-dust mixture that is achieved prior to ignition. In each trial there is a varying amount of coal dust that is entrained into the atmosphere due to the layered deposition of the dust sample. This is indicative of unique atmospheric conditions for each underground coal mine, where geologic, mining, and ventilation factors will affect the deposition rate and bed thickness of float coal dust.

Fig. 12 shows the results of the peak explosive pressure for the lean explosibility tests between the 20 and 38 L chambers. The 20 L chamber data was taken from the work conducted by Cashdollar and Hertzbeg [7]. A 2nd order polynomial regression line was fitted to the data for each test series. It is clear that for concentrations greater than 400 g/m^3 in both explosive chambers, the maximum explosive pressure exceeds the first criterion of significant flame propagation that was set forth by the USBM. While there is difference in the data due to the dispersion method, both chambers were able to achieve significant flame propagation, which would create a coal dust explosion. The variable mixture within the 38 L chamber generates a wider range of variability for explosive pressure when compared to the 20 L chamber used by the USBM which ensures a thorough mixture by its design.

Fig. 13 shows the calculated K_{st} values from a test series conducted by the USBM [7]. The test series used coal dust concentrations in a range from 50–1000 g/m^3. The maximum K_{st} using the 20 L chamber was approximately 3600 kPa m/s using a coal dust concentration of 600 g/m^3, and begins to decrease in value as the coal dust concentration increases. Based upon the results that were calculated, all of the trials in this test series would fall into the "St 1" category, which signifies a weak explosion within the chamber.

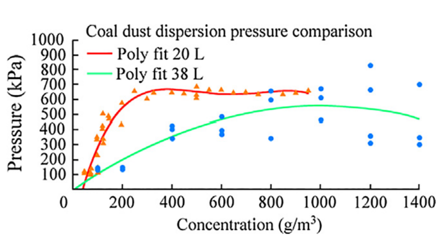

Fig. 12. Coal dust explosion test peak pressures comparison between 20 and 38 L chambers.

Fig. 14 compares the K_{st} index values between the two data sets. After inspecting the data, there is significant difference in the explosive index between the two chambers. The data from the 20 L chamber shows significantly higher values of K_{st}, and overall there is more variability within the test series. The maximum K_{st} using the 38 L chamber was approximately 800 kPa m/s using a coal dust concentration of 1200 g/m^3, and then begins to decrease with increasing concentration.

When using the Occupational Safety and Health Administration (OSHA) dust explosion index shown in Table 1, to categorize the dust explosion results, all trials from both test series fall in the "St 1" category, and would generate a weak explosion. However, when using the criteria for significant flame propagation there is discrepancy between the two data sets. The K_{st} for significant flame propagation was set by the USBM to be 150 kPa m/s. When using this criterion, the minimum concentration necessary for significant flame propagation using the 20 L chamber was approximately 100 g/m^3, but using the 38 L test chamber, this was not achieved until a concentration of 600 g/m^3 was tested.

When comparing the peak pressure results and the K_{st} index results between the two chambers, there are general trends that can be observed. The results of the 38 L test series have lower values when compared to the 20 L results of the same coal dust concentration. This is due to the composition of the atmosphere within the explosive chamber at ignition. The 20 L chamber places the coal dust directly below the dispersal nozzle located at the bottom of the chamber. This ensures that all of the dust is dispersed within the chamber prior to ignition, resulting in a thorough air-dust mixture. The 38 L chamber places the coal dust into a tray container, located in the center of the explosive chamber. This creates variability in the amount of coal dust that is dispersed into the chamber prior to ignition, which generates a variable atmosphere.

This method of dispersal is more representative of coal dust entrainment by explosive airflow due to the unique requirements of coal mines to use rock dust as an inerting agent in the case of an explosion. Dust layers are deposited in distinct beds, and have different dispersal characteristics than other industries where combustible dust explosions can occur that may be more suitable for testing in the standard Siwek chamber.

6. Conclusions

Combustible dusts present a hazard for a number of industries including: agriculture, chemicals, pharmaceuticals, and coal mining. There are a number of standardized tests to determine the atmospheric conditions that allow for a dust explosion to occur. An explosive index, K_{st}, has been developed by government agencies to address the explosive potential of a combustible dust. All of these tests involve using an explosive chamber of known volume and using pressurized air to disperse the dust within the chamber to a thorough air-dust mixture prior to igntion. However, this complete mixture is not representative of what would be created in underground coal mine explosion.

Underground coal mining is unique due to the process of adding inert limestone dust overtop of coal dust to act as a heat sink in the event of an explosion. This limestone dust should prevent underlying coal dust from re-entraining into the atmosphere. This may not always happen due to conditions present at the mine, but that is outside of the scope of the research presented in this paper. However, during active mining float coal dust is generated and deposited on the rock dust layer. Occasionally, a new layer of rock dust will be deposited on top of the float dust, and the cycle is repeated. This creates distinct layers of rock dust and coal dust. This layered deposition scheme has additional methods of dispersion when subjected to explosive airflow. Due to various geologic and mining factors, the atmosphere of an underground coal mine will most likely not contain a complete air-dust mixture before the propagating explosion causes ignition of the float coal dust.

To account for this variable mixture, a series of lean explosibility tests was conducted on Pittsburgh Pulverized coal dust in a 38 L explosive chamber. This chamber alters the location of the pressurized air nozzle such that the air is blown over top of the dust sample, which creates variability in the amount of dust entrained into the chamber prior to igntion. In total, 24 tests were conducted with the 38 L chamber. The overpressure ratio and K_{st} parameter were recorded and compared to values obtained by the Bureau of Mines using a 20 L explosive chamber that is used for standardized combustible dust tests.

When comparing the results of the test series, it is clear that the 38 L chamber generated lower overall explosive pressure, however at concentrations greater than 1000 g/m^3, there is a large amount of variability in the peak pressure. This may be attributed to the non-uniform mixture of coal dust and air within the explosive chamber which is likely to occur in underground coal mine environment. When comparing the K_{st}, the values are also lower than compared to the 20 L chamber, but there is no difference in the characteristic explosion classification. All of the tests conducted between the two explosive chambers would be categorized as a "weak explosion" having a K_{st} value between 0 and 200 according to OSHA.

Additional analysis of the 38 L explosive chamber should still be conducted. Analysis of a layered bedding scheme should be investigated, using uniform thickness layers of rock dust and coal dust. This testing would determine if only float coal dust would be entrained into the mine atmosphere at the time of ignition, or if underlying layers would contribute due to the longitudinal regression dispersal mode. This could be used to then study the effects of lean explosibility of coal dust with variable deposition bed thicknesses which would represent the conditions within an underground coal mine.

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