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Research Article

Evaluation of a 38 L Explosive Chamber for Testing Coal Dust Explosibility

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Coal dust explosions are the deadliest disasters facing the coal mining industry. Research has been conducted globally on this topic for decades. The first explosibility tests in the United States were performed by the Bureau of Mines using a 20 L chamber. This serves as the basis for all standardized tests used for combustible dusts. The purpose of this paper is to investigate the use of a new 38 L chamber for testing coal dust explosions. The 38 L chamber features design modifications to model the unique conditions present in an underground coal mine when compared to other industries where combustible dust hazards are present. A series of explosibility tests were conducted within the explosive chamber using a sample of Pittsburgh pulverized coal dust and a five kJ Sobbe igniter. Analysis to find the maximum pressure ratio and K_{st} combustible dust parameter was performed for each trial. Based upon this analysis, observations are made for each concentration regarding whether the explosibility test was under-fueled or over-fueled. Based upon this analysis, a recommendation for future explosibility testing concentrations is made.

1. Introduction

Coal dust explosions are among the deadliest mining disasters. The Mine Health and Safety Administration (MSHA) classifies any mining accident that claims at least 5 lives as a mining disaster [1]. Since 1970, 21 coal mine disasters have taken place in the United States, causing a total of 261 fatalities. Among these disasters, 15 have been classified as explosions, totaling 201 fatalities. Prevention of coal dust explosions has been studied globally for decades [2].

Experiments in coal dust explosibility were a primary concern of the United States Bureau of Mines (USBM) [3]. The first full-scale tests of coal dust explosions began in 1910 with the newly created USBM working in conjunction with the Mining Association of Great Britain at the Altofts colliery in Yorkshire [4]. However, there were a number of technical difficulties with performing repeated full-scale tests at the site [4].

The USBM then set out to develop testing procedures for laboratory-scale testing. The first explosive chamber was developed by the USBM and was eight liters (L) in volume which was based upon a chamber that was previously developed for explosibility studies of homogenous gas mixtures [5]. The primary concern with this chamber was the limited amount of realized ignition energy due to the low volume of the chamber.

The standard testing procedure, per ASTM E1226, uses a 20 L volume chamber based on the design used by Siwek [6]. These standardized tests have been developed to investigate the explosibility of coal dust and the atmospheric conditions that are indicative of an explosion. These tests are used in a number of industries where combustible dust explosion hazards are possible. The basic principle behind the test procedure is to combust a known amount of dust within an explosive chamber of the known volume. This chamber is comparable to the Bartknecht 1 m^3 standard test chamber used in Europe [7]. When using the Bartknecht chamber, explosive dust 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 semiannular, 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 [7].

A sample of coal dust is placed in a container underneath the chamber where a pressurized air pulse is injected to disperse the dust throughout the chamber prior to the ignition of the sample. Optical dust probes, oxygen sensors, and pressure transducers are used to monitor the conditions within the chamber throughout the entire test procedure. The results of these tests are reported in terms of the overpressure ratio and the rate of pressure rise with respect to time. The overpressure ratio is defined as the maximum recorded pressure divided by the pressure at detonation. There are currently two standards that are used to evaluate whether an explosion occurred and the intensity of the explosion [8, 9].

These criteria were first developed by Cashdollar and Hertzberg [9]. There are two conditions that are indicative of an explosion occurring within a test chamber: (1) the pressure ratio be greater than 200 kPa and (2) the cubic root of the volume-normalized pressure time derivative (K_{st}) be greater than 150 kPa·m·s^{-1}. Other classification techniques for combustible dust explosions utilize the K_{st} parameter which is based off the second criterion. The pressure ratio is defined as the maximum recorded explosive pressure normalized by the pressure at the time of initiation. To simplify the calculation, all detonations were initiated at a pressure of 1 bar (~101 kPa). This allows the air pressure ratio to be equivalent to the maximum explosive pressure recorded during each experimental trial.

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 (Occupational Safety and Health Administration (OSHA), Factsheet 2015). Similar 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 [8].

In this research, a series of coal dust explosibility tests were conducted using a new 38 L chamber, which is modeled after the standard 20 L chamber [10]. The primary design modification for this chamber is the placement of the dust sample within the chamber relative to the pressurized air pulse. In all explosibility tests, a 5 kJ Sobbe igniter was installed into the chamber to test the explosibility of the coal dust sample.

Twenty-five tests were conducted in the explosive chamber. The results of these tests in terms of overpressure ratio and K_{st} were compared to previously published data using the 20 L chamber.

2. Materials and Methods

2.1. Explosive Chamber and Experimental Setup. Coal dust explosion test trials were performed using the 38 L chamber, as shown in Figure 1. The explosive chamber was constructed from 308 steel and has a wall thickness of 9.525 mm. The chamber was constructed and tested by Materials Engineering and Testing Corporation and approved to accept pressures up to 2,068 kPA [10]. A schematic of the 38 L chamber is shown in Figure 2.

The explosive chamber has a length of 61 cm with an inside diameter of 30.5 cm, which results in an L/D ratio of two. This is a deviation from the standard 20 L test vessel having an L/D ratio of one. The explosive chamber was designed with these dimensions to simulate the physical dimensions that are common in underground coal mines [10]. Specifically, this allows the coal dust sample to be placed in front of the air nozzle so that the air pulse passes directly over the sample. This was done to simulate the float coal dust conditions that are typical in an underground coal mine environment.

In an underground coal mine, there are long entryways that are developed by the mining crew. Coal dust is liberated from the seam during the mining process and is deposited on the floor of these entries. If an explosion occurs within an underground coal mine, the pressure wave will pass over loose or "float" coal dust within the entry and entrain the dust within the air, instead of dispersing the sample by passing underneath the dust.

The 38 L chamber is instrumented with an Omegadyne PX-409 piezolectic sensor. This sensor outputs a voltage between 0 and 10 V, which is then converted into an absolute pressure reading between 0 and 1.72 MPa. This sensor was chosen for its high standard measuring accuracy. The Omegadyne PX-409 sensor has a ±0.08% best straight line (BSL) accuracy with appropriate sensitivity to support this accuracy. The sensor is located directly above the coal dust sample within the chamber. A 5 kJ Sobbe igniter was used inside the chamber to initiate the coal dust explosion.

The Sobbe pyrotechnic igniter is specifically designed for use in explosibility tests of dust, gas, and hybrid mixtures [11]. The pyrotechnic charge is placed in a plastic shell that is then placed inside an aluminum casing. The 5 kJ igniter was selected in order to keep in line with the conditions that previous research investigations have been conducted using the 38 L chamber [12]. The Sobbe igniter is installed directly in the chamber in front of the dust sample to ensure that the energy from the igniter is imparted to the liberated dust cloud.

Eight different sample concentrations were chosen for the explosibility tests. Each of these concentrations had three experimental trials (except for one case, which had four trials). This results in a total of 25 tests. All of these experimental tests used increments of a 7.6 g of coal dust. When normalized to the volume of the explosive chamber, this equates to concentration increments of 200 g/m^3. Experiments ranged from 200 g/m^3 to 1,400 g/m^3. Additionally, a set of tests were conducted at a concentration of 100 g/m^3 to investigate the effects of very small coal dust concentrations [10]. A 4th trial was conducted at a concentration of 1,200 g/m^3 due to wide variation in the recorded peak pressure. This will be discussed in a later section of this paper.

Figure 1: 38 L explosive chamber [9].

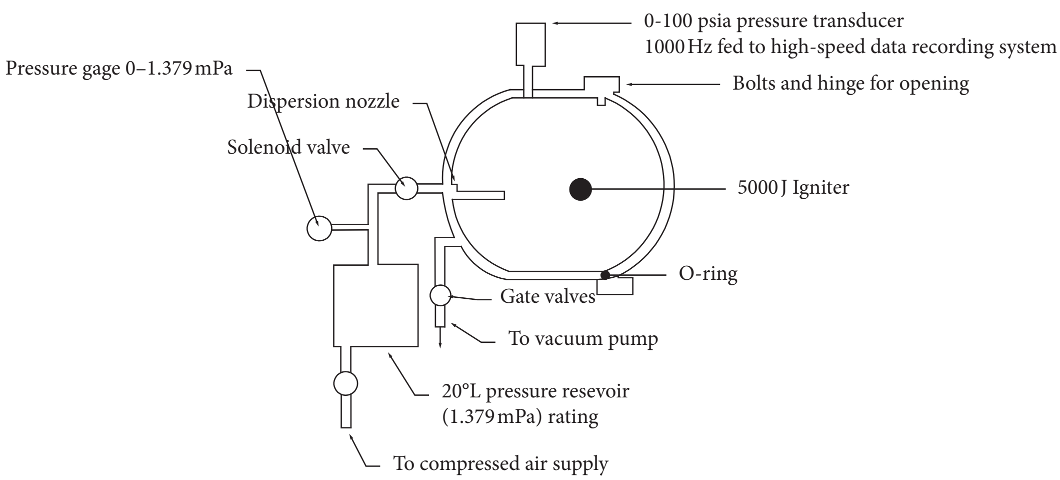

Figure 2: Schematic of the 38 L explosive chamber [9].

To conduct the explosibility tests, the coal dust samples are placed on an aluminum tray and installed within the chamber. Figure 3 shows a coal dust sample that has been installed into the 38 L chamber prior to testing.

Once the sample and igniter were installed, the chamber was been sealed and a vacuum pump was activated. The chamber was drawn down to an absolute pressure of approximately 14 kPa [13]. Simultaneously, a pressure reservoir used to disperse the coal dust was filled to 1,034 kPa. Previous research has shown that a pressure of 965 kPa was required for the 20 L chamber [9]. A higher pressure was chosen for the pressure reservoir due to the increased volume of the explosive chamber. Once the target pressure inside the chamber was achieved, the pressurized air pulse was released into the chamber to disperse the coal dust through the nozzle, as shown in Figure 3. Once the pressure in the chamber returned to atmospheric levels (~101 kPa absolute), the igniter was fired.

Software was developed in the LabVIEW environment to control the various processes within each test and to record the pressure achieved within the explosive chamber [13]. For these explosibility tests, a detonation is considered to have occurred if either of the two criteria that were previously discussed are achieved.

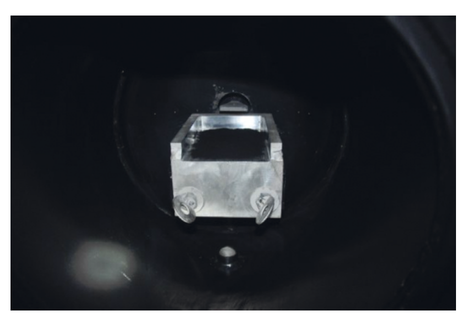

Figure 3: Sample tray installed in the 38 L explosive chamber [9].

2.2. Coal Dust Data. All experimental trials conducted in this research used a sample of Pittsburgh pulverized coal dust. The results of the sieve analysis for this sample are shown in Table 1 and graphically displayed in Figure 4. The

Table 1: Sieve analysis of the Pittsburgh pulverized sample [8].

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

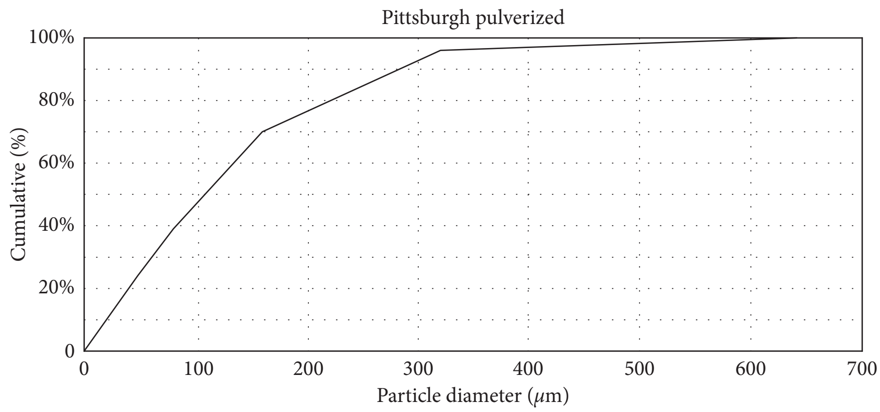

Figure 4: Particle size analysis for the Pittsburgh pulverized coal dust sample.

results of the analysis show that the 50% passing size for the sample was 102 μm. Proximate analysis of the coal dust was performed, and the results are provided in Table 2.

It should be noted that the reported volatility is for reference only. Other research has shown that true volatilities are higher with the high heating rates that are found in combustible dust explosions [14, 15].

Table 2: Proximate analysis of the Pittsburgh pulverized sample.

Coal dust	Moisture (%)	Ash (%)	Volatility (%)	Fixed carbon (%)
Pittsburgh	0.9	6.1	36.5	56.6

3. Results and Discussion

Figure 5 shows an ideal curve for the coal dust experiments. Each experiment can be divided into three distinct pressure regions: (1) initial vacuum stage, (2) pressurized air injection, and (3) detonation. However, due to the wide range of tested concentration levels, it is possible that some of the samples were under-fueled and others were over-fueled. Figure 6 shows a comparison of under-fueled and over-fueled explosibility tests.

An under-fueled explosibility test of the coal dust sample is characterized by a small pressure rise, followed by a quick return to atmospheric levels. This indicates that there was an abundance of oxygen within the chamber, and deflagration of the sample occurred, not detonation. There is evidence of this deflagration occurring at a concentration level of 100 and 200 g/m^3 in the 38 L chamber.

An over-fueled explosibility test is characterized by incomplete detonation of the coal dust sample. This is because there is not enough oxygen present within the chamber to allow for complete detonation. This is seen in the 38 L chamber as the coal dust concentrations go above 1000 g/m^3. At this point and beyond the maximum explosive pressure and K_{st} values begin to level out, no significant increase is seen for higher coal dust concentration levels. Another sign of an over-fueled detonation is the ambient pressure level within the chamber after the test; if coal dust remains within the chamber after the test, the pressure within the chamber will be significantly higher than standard atmospheric pressure.

Additionally, there is more variance in the data, which is again due to the high concentration levels, as shown in Figure 7. The material may not be thoroughly mixed into the explosive chamber when atmospheric pressure is achieved, and detonation occurs. This will create pockets within the explosive chamber where there is a high concentration of coal dust and others where there is relatively little coal dust. If the coal dust sample was evenly dispersed throughout the volume of the explosive chamber prior to detonation, the measured pressure and K_{st} values would be higher for higher concentrations.

Preliminary inspection of the raw data shows that there is an upward trend in maximum pressure with increasing dust concentration. However, there is also increasing variance in the data as the concentration continues to increase. This variance is the reason that a 4th trial was conducted at 1200 g/m^3.

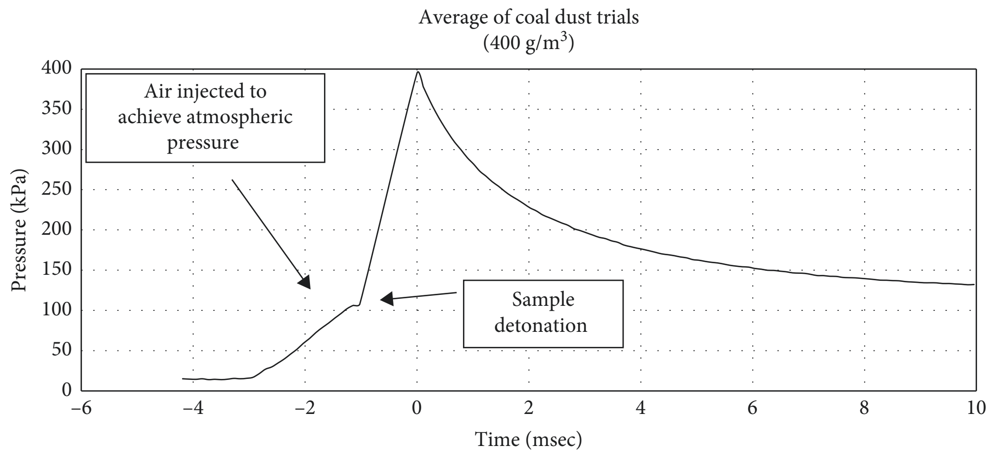

Figure 5: Idealized coal dust test.

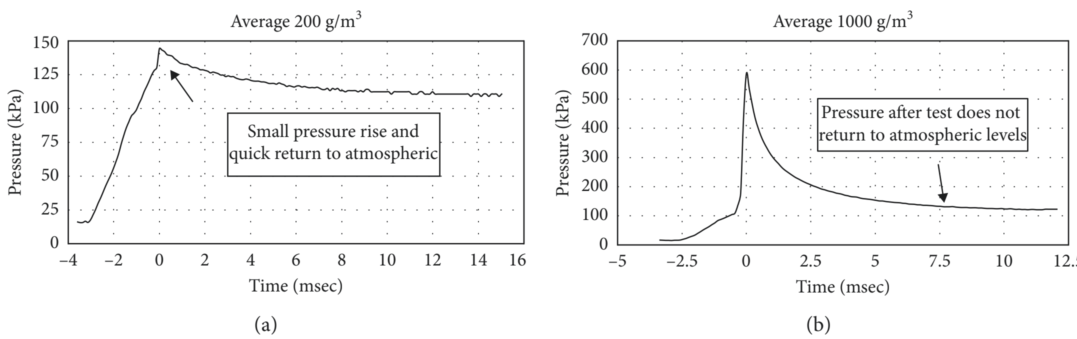

Figure 6: Comparison of under-fueled (a) and over-fueled (b) coal dust tests.

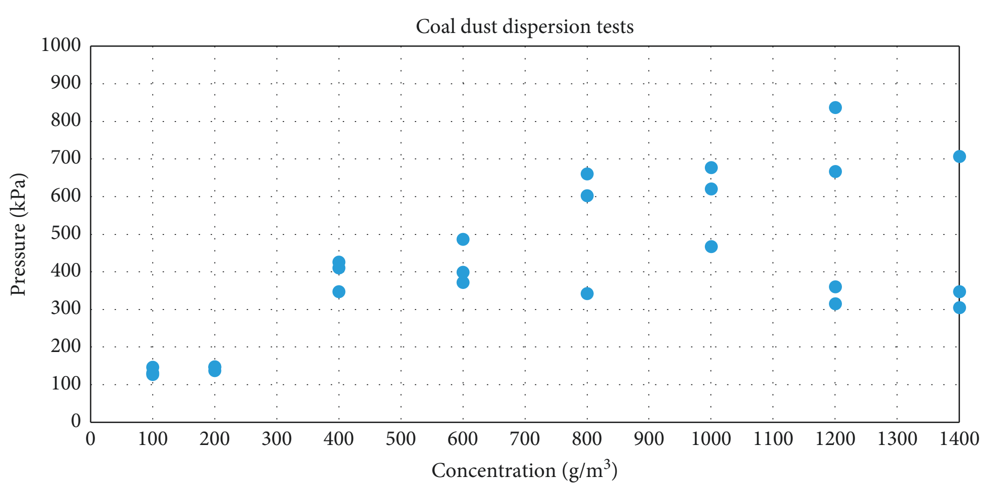

Figure 7: Coal dust explosibility tests (adapted from [10]).

After inspecting the pressure data gathered during the experiments, calculations were performed to determine if a significant explosion occurred within the chamber. The pressure data were imported into a graphing software package, and then a numerical time derivative was performed. The final step was to then find the maximum pressure derivative value for each coal dust concentration and apply the following formula to find the K_{st}:

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

where dP/dt is the pressure derivative with respect to time and $V^{1/3}$ is the cubic root of the volume.

The results of the analysis for all eight coal dust concentrations are shown in Table 3. After inspecting the table and comparing the results of the analysis to the aforementioned

Table 3: Explosion criteria analysis.

Coal dust concentration (g/m^3)	Maximum pressure ratio (kPa)	K_{st} (kPa·m∗s^{-1})
100	129.23	49.27
200	144.38	54.09
400	309.6872	313.07
600	419.1	443.64
800	535.56	818.85
1000	588.31	847.77
1200	545.1	1090.17
1400	453.34	898.98

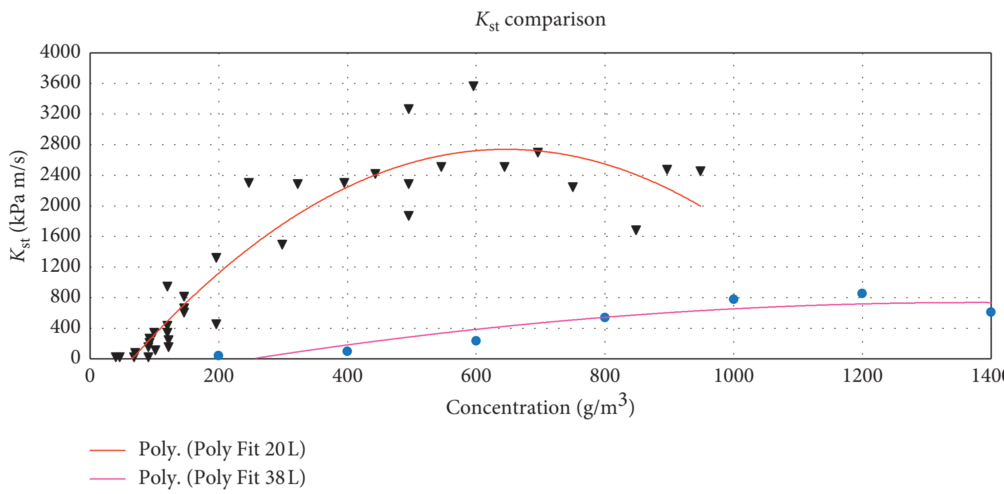

Figure 8: Comparison of K_{st} values from explosibility testing using 20 L and 38 L chamber designs (adapted from [16]).

criteria for explosion assessment, it is clear that several of the dust concentration levels were successfully detonated within the 38 L chamber. However, there are two dust concentrations that were not detonated. For both of these concentrations, neither of the two criteria for detonation were achieved. They are 100 g/m^3 and 200 g/m^3, respectively. As previously mentioned, they are also the concentration levels that show evidence of being under-fueled, which is further supported by the evidence that detonation did not occur within the chamber for these tests.

Another trend can be seen when inspecting the maximum pressure ratio. As the coal dust concentration within the chamber increases, so too does the maximum pressure ratio, until a concentration of approximately 1,000 g/m^3. At this point, the maximum pressure achieved within the chamber begins to level off with increasing coal dust concentration levels. This is indicative of an over-fueled explosibility test because of the varying amounts of coal dust that are deflagrated, due to insufficient oxygen, before the conditions within the chamber allow for detonation.

The K_{st} parameter continues to increase beyond this point. The inflection point for K_{st} is located at the 1200 g/m^3 concentration level and further supports that the explosive chamber becomes over-fueled at the higher concentration levels. Based on the established criteria for combustible dust tests in an explosive chamber and the analysis conducted on this series of explosibility tests, the research team has determined a range of recommended concentration levels for the 38 L chamber. The recommended concentration levels for explosibility tests conducted in the 38 L chamber should be between 400 and 1,000 g/m^3.

It should also be noted that there is a significant increase in the K_{st} parameter when using a concentration of 800 g/m^3, and this is most due to the increased amount of coal dust within the explosive chamber. The increasing amount of coal dust will cause a larger variation in the composition of the air-dust mixture within the chamber. As the amount of coal dust within the chamber continues to increase, this will begin to approach the thorough mixture conditions that are present within the 20 L chamber prior to detonation.

In summary, the design modifications of the 38 L chamber have a noticeable effect on the measured K_{st} values when using the standardized test method for combustible gas mixtures. These modifications more accurately represent the unique conditions in an underground coal mine that are not tested in the 20 L explosive vessel, which is designed for other industries (agriculture, pharmaceuticals, etc.) where a dust explosion hazard is also present. The effect of these design alterations is made clear when comparing the K_{st} values obtained when conducting explosibility tests using the standard 20 L chamber.

Figure 8 shows the comparison of the K_{st} values when using the 20 L chamber compared to the 38 L chamber. This data was obtained from the USBM series that was conducted by Cashdollar and Hertzberg [16]. After inspecting the data, it is clear that a thorough mixture of the coal dusts into the air sample will create a stronger detonation; however, it cannot be assumed that the dust-air mixture will be thoroughly mixed prior to detonation in an underground coal mine.

4. Conclusions

Coal dust explosions are some of the deadliest disasters in the mining industry. Decades of research have been conducted to improve understanding of the conditions that must be present for a coal dust explosion to occur. The most common method of testing the explosibility of coal dust is detonating a known amount within an explosive chamber of known volume. The standardized test developed for combustible dusts utilizes a 20 L chamber. An experimental investigation was performed to analyze a new 38 L volume chamber with a number of design modifications to model the unique conditions present within an underground coal mine.

Using the developed standardized testing procedure, testing was performed on eight different concentrations of coal dust. In total, 25 trials were conducted. The results of the trials were analyzed to find the average maximum pressure for each concentration level and the K_{st} combustible dust parameter. This analysis allows for direction comparison of previously published criteria for classifying detonation and detonation intensity.

Based upon this comparison, the 100 g/m^3 and 200 g/m^3 concentration levels failed to detonate. Close inspection of the pressure data obtained from these trials reveals that the explosibility tests were under-fueled. Conversely, pressure data obtained from 1200 g/m^3 and 1400 g/m^3 shows that increasing concentration of coal dust resulted in no significant increase in maximum pressure. This is because there was insufficient oxygen within the explosive chamber to cause detonation of the sample. This is indicative that the explosibility tests conducted at these concentrations were over-fueled. Therefore, it is recommended that any explosibility tests conducted within the 38 L chamber have combustible dust concentrations between 400 and 1000 g/m^3.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. The raw data are also available in the corresponding author's master's thesis.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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