Hazard evaluation of sulphide dust explosions

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Abstract

Experiments were conducted in a 1 m^3 explosion chamber and the explosibility parameters for sulphide dust were determined and compared to other types of dusts. The severity of the explosions, as indicated by the K_{St} value, was scaled by comparing the experimental results from different sizes of explosion vessels. The K_{St} value was found to increase with the volume of the explosion chamber, as expected for systems whose level of turbulence increases with increasing chamber volume. Explosive limits for a typical sulphide dust were obtained by examining the effect of dust concentration on the explosibility parameters. The lower explosive limit was found to be 300 g/m^3 for a sulphide dust with a sulphur content of 29.86% by weight. To simulate the ignition source in underground mines, explosives were used to ignite sulphide dust clouds in the 1 m^3 chamber tests and an ignition criterion was developed for mining explosives that do not contain aluminum. It was found that the minimum ignition energy can be expressed as the product of the heat of explosion and the minimum weight of explosive required for the ignition of the dust.

1. Introduction

Sulphide dust explosions in underground sulphide mines have been reported frequently during the last twenty years. In most cases, dust explosions occur when blasting in massive sulphide ore bodies. The blasting operations generate a considerable amount of dust by crushing the ore immediately around the boreholes and during the fragmentation process of the friable sulphide ores. The exhausting heat and/or hot particles resulting from the detonation of the explosives used for blasting may provide enough energy to ignite the dust cloud and create a primary dust explosion. This might be followed by a secondary dust explosion in which the dust lying on the walls of the opening is dispersed by the pressure wave produced by the primary explosion and ignited

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by the flame front. The explosion could propagate long distances as long as the amount of dust to be dispersed is enough to feed the combustion process.

From the chemical point of view, a sulphide dust explosion is a rapid oxidation process of the sulphide minerals. For instance, the dust explosion of pyrite (FeS_2), which has been found to be frequently related with explosion occurrences, can be expressed by the following reaction under confined condition [1]:

$$3\,FeS_2 + 8\,O_2 \rightarrow Fe_3O_4 + 6\,SO_2 + 6.58\ kJ/g\ of\ FeS_2 \tag{1}$$
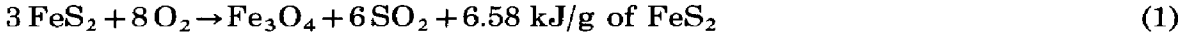
This typical reaction indicates three characteristics of a sulphide dust explosion:

(1) A large amount of heat is produced.
(2) The number of moles of gas after an explosion is less than the number before.
(3) The gaseous product (SO_2) is extremely toxic.

The first two characteristics implicate that the explosion pressure rise is caused by the temperature rise in the explosion products. The destructive force to underground facilities may be very violent in the region close to the explosion but the overpressure will decay when temperature drops. Furthermore, the generation of SO_2 gas has been one of the major problems in underground operations because the SO_2 gas must be diluted below the regulation level (2 ppm) before miners re-enter the mine.

In this paper the violence of sulphide dust explosions is compared with other dust explosions and scaling of the explosion hazard is discussed. The necessary conditions for a dust explosion are also examined in terms of dust concentration and ignition energy with explosive type of ignition sources.
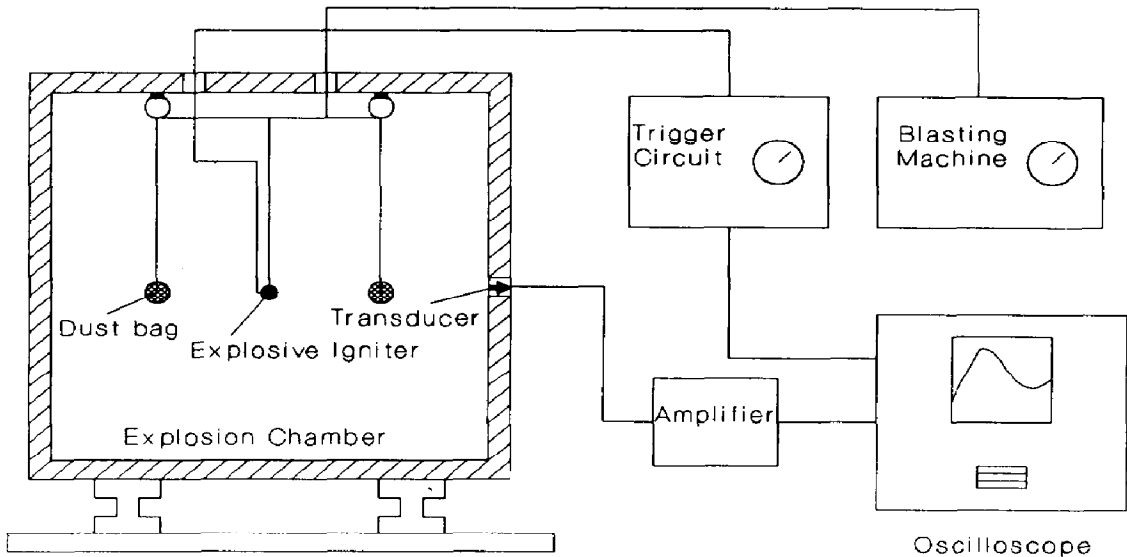

Fig. 1. Explosion monitoring system.

2. Experimental techniques

Experiments on the dust explosibility were conducted in a 1 m³ explosion chamber. The wall of the cubic chamber is made of 12.7 mm thick steel plates and reinforced by two rows of box-beams at each side in both directions. The door can be tightly closed using 20 bolts. A rubber gasket is placed at the flange of the chamber so that no explosion products are released after the explosion.

Figure 1 illustrates the experimental arrangement. The dust is dispersed using four bags in which seismic detonators detonate instantaneously by means of a high voltage firing machine (Cordin 470). The explosive charge which is used to ignite the dust is placed at the centre of the chamber and fired with a zero delay detonator which gives an actual delay time of about 5–8 ms. By this time the dust cloud has been formed fully as observed using high speed photography. For the recording of the explosion pressure a Kistler pressure transducer (model 603B), mounted at the centre of a side wall of the chamber, is used. This is connected via a low-noise coaxial cable to an amplifier (Kistler dual mode 5004) and a Nicolet oscilloscope (model 4094). The recorded pressure history is corrected for the effect of the explosive igniter.

Two types of sulphide dust were used in the experiments; Type I and Type II. Type I is a typical sulphide dust which was provided by a Canadian sulphide mine. Its composition is 44.9% pyrite, 15.8% sphalerite, 4.8% galena, 1.1% chalcopyrite and 33.4% gangue material by weight. The sulphur content is
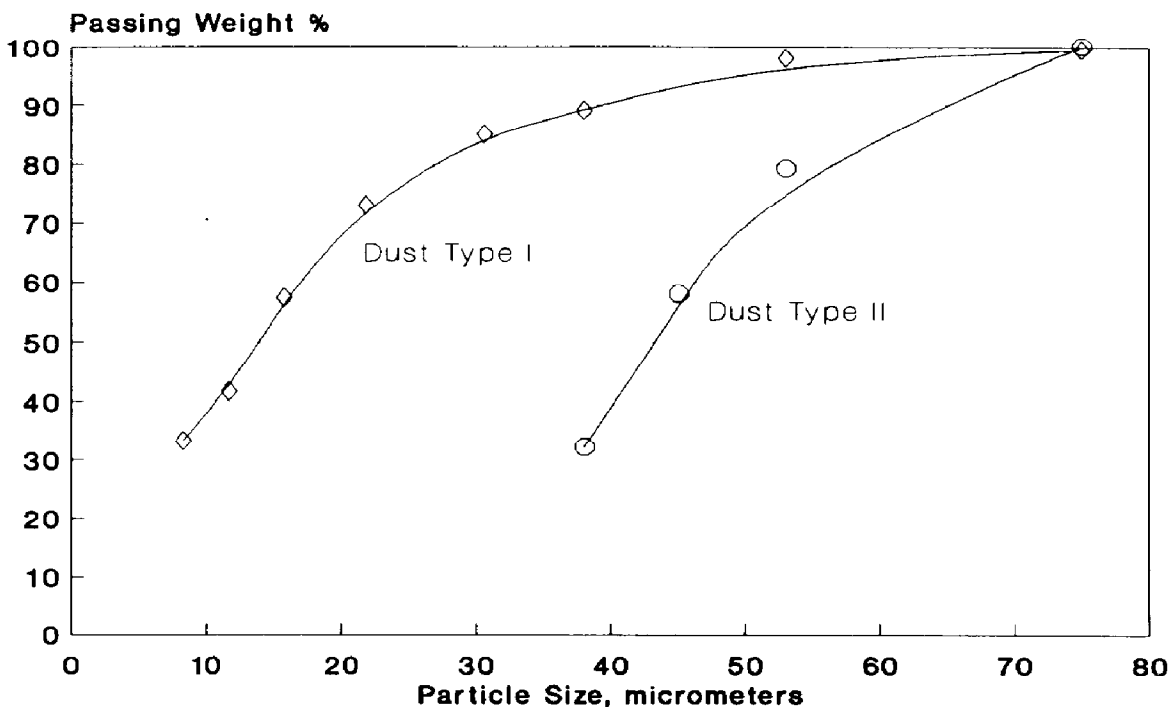

Fig. 2. Particle size distribution of the sulphide dusts used in experiments.

29.86%, the measured density of the dust particles is 3.90 g/cm^3 and the specific surface area is 1.34 m^2/g. The size distribution of the dust sample is shown in Fig. 2 while the overall mean size is 14 μm. Sulphide dust Type II was ground from a pyrite ore sample to < 75 μm (−200 mesh) and had a sulphur content of 47.9% by mass. The size distribution of the dust used in the experiment is also shown in Fig. 2. The density of the particles is 5.04 g/cm^3 and the mean size is 43 μm.

3. Relative explosion severity of sulphide dusts

Figure 3 shows typical recorded pressure histories for three dust explosions: cornstarch, wheat flour and sulphide dust Type I. Cornstarch and wheat flour were used to test the explosion chamber, as well as the recording system. Strong igniters were used to ignite the clouds: 6 g Detasheet (a military explosive consisting of pentaerythrol tetranitrate and a plastic binder) for cornstarch and wheat flour, and 15 g for the sulphide dust. The magnitude of the explosion pressure and the rate of pressure rise can be obtained directly from the recorded traces. The relative explosibility is, however, established through a classification system.

The U.S. Bureau of Mines [2] proposed a methodology for estimating industrial dust explosion hazards in terms of three probabilities: The dispersion of dust, the existence of a flammable dust concentration and the presence of an
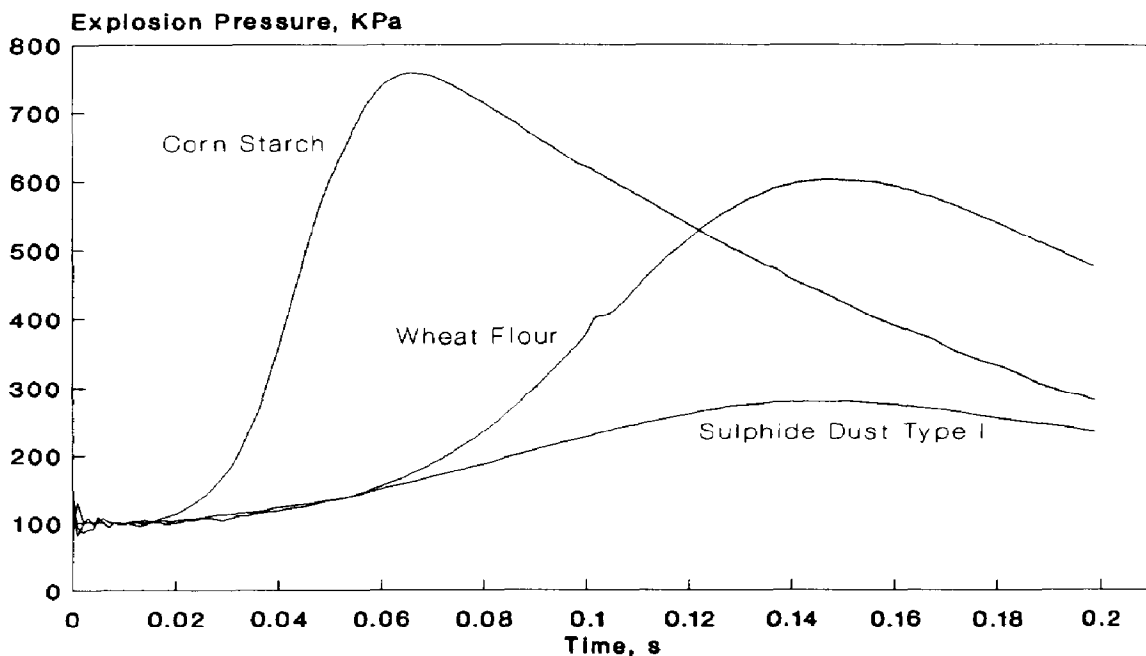

Fig. 3. Pressure–time recording of dust explosions.

effective source of ignition. This method is logical and the assessment must be done systematically in order to quantify the explosion hazard for a particular facility.

Another method which is commonly used [3], uses the K_{St} value which is obtained by the cubic relationship [3]:

$$\left(\frac{dP}{dt}\right)_{max} V^{1/3} = K_{St} \tag{2}$$

where $(dP/dt)_{max}$ is the maximum rate of pressure rise; V is the volume of explosion vessel; and K_{St} is a constant for a particular dust.

This formula indicates a fundamental observation that the maximum rate of pressure rise, which reflects the violence of a dust explosion, decreases with a larger volume of explosion vessel. For a particular dust, the K_{St} value is expected to be a constant. A four-class severity classification system has been established by grouping the K_{St} value in four ranges [3]. According to this system, St-0 class contains non-explosive dusts (K_{St} equal to 0), St-1 class contains dusts exhibiting "weak" explosion characteristics (K_{St} between 0 and 20 MPa m/s), St-2 class contains dusts exhibiting "strong" explosion characteristics (K_{St} between 20 and 30 MPa m/s), and St-3 class includes dusts exhibiting "very strong" explosion characteristics (K_{St} larger than 30 MPa m/s).

It should be noted that dust explosion hazard classification is established for designing surface facilities, e.g. relieving vents, in grain and other processing industries. The magnitude of an explosion hazard in this case is usually more severe than that of sulphide dust in underground mines. However, the rating helps to understand how violent a sulphide dust explosion is, compared to other combustible dusts. The designated parameters also help to compare the severity between different sulphide dusts.

Table 1 compares the explosibility parameters for sulphide dust Type I and Type II, as well as cornstarch and wheat flour. The data for cornstarch and

TABLE 1

Comparison of explosibility parameters obtained from 1 m^3 explosion chamber

Parameters	Cornstarch	Wheat flour	Sulphide dust Type I	Sulphide dust Type II
Dust concentration (g/m^3)	500	500	600–1000	600–1000
P_{max}(kPa)	786	603	230–302	330–370
$(dP/dt)_{max}$(MPa/s)	25.56	7.30	1.2–2.3	3.5–7.0
Time of peak pressure (ms)	66.5	147	130–170	65–93
K_{St} Value (MPa m/s)	25.6	7.3	1.2–2.3	3.5–7.0

wheat flour were directly read from the recordings of Fig. 3. For sulphide dusts Type I and Type II, because a large number of tests has been conducted, the range of typical readings is given for the major parameters. It is obvious that cornstarch and wheat flour give higher explosion pressure and rate of pressure rise than sulphide dusts. According to the dust explosion classification system based on the K_{St} values [3], sulphide dusts fall into the St-1 class. It was found that the K_{St} constant is in the range of 1.2–2.3 MPa m/s for sulphide dust Type I and in the range of 3.5–7.0 MPa m/s for sulphide dust Type II. In both cases the major sulphide mineral is pyrite. However, the concentration of pyrite is larger in sulphide dust Type II.

The major difference between cornstarch and wheat flour dusts is in the particle size. Cornstarch consists of very fine particles (mean size 22 μm) while the enriched wheat flour consists of much coarser particles (mean size 80 μm). The compositions are, however, similar. It is clearly demonstrated that the explosion pressure and the rate of pressure rise increase when the particle size is decreased. This, however, has been well established for a variety of other materials [3,13]. As far as the tested sulphide dusts are concerned, Type II dust shows higher explosibility than Type I dust. Type II dust is, however, coarser than Type I dust. Therefore the difference between the dusts, which is a result of the difference in their chemical composition would be more marked for a finer Type II dust.

From the magnitude of P_{max} and $(dP/dt)_{max}$, it is apparent that a sulphide dust explosion is less violent than the explosion of carbonaceous dusts such as cornstarch and wheat flour. Compared with other combustible dusts in underground mines, sulphide dust is also less hazardous than bituminous coal dust and higher grade oil shale dust, but it is comparable to low grade oil shale and higher volatility (7%) anthracite dusts [4]. However, for sulphide dust explosions, the additional problem is the toxic gas SO_2 that causes production delays in underground mining operations.

4. Scaling of sulphide dust explosions

In many cases when comparing the explosibility results obtained from small vessels with those from large vessels, the K_{St} value, as expressed by eq. (2) is not constant. There is a minimum volume of explosion vessel to produce a constant K_{St} value [3]. In other words, the explosibility results from small vessels may not be representative for the evaluation of the dust explosion hazard. For sulphide dusts, experiments on the explosibility have been conducted by researchers in several countries using different sizes of explosion vessels. It is certainly necessary to compare these results and scale the hazard of sulphide dust explosions. However, only few vessel sizes have been used for sulphide dusts and further, there is a lack of standardization on the methods of dust dispersion and ignition. These factors make it difficult to fully investigate the scaling of sulphide dust explosions.

Table 2 gives the explosion pressure and rate of pressure rise obtained from different explosion vessels. The listed values are the highest from the particular source. The particle sizes of these sulphide dusts are all finer than 75 μm. Since sulphide dust Type I and Type II have been used by several researchers, results are comparable. Bituminous coal dust is also listed for the purpose of comparison.

For sulphide dust Type I, it was found that the peak explosion pressure does not change significantly with the size of the explosion vessel, whereas the maximum rate of pressure rise does. It is generally true that higher $(dP/dt)_{max}$ is produced from smaller vessels. However, the K_{St} value, and subsequently the explosion hazard, is found to be smaller in small vessels. In other words, smaller vessels seem to under-estimate the explosion hazard. This is a clear indication that the K_{St} values obtained from vessels having volume smaller than 20 L, do not represent the real hazard rating for sulphide dusts. A proper interpretation and scaling is required to correlate the data for protective designs in underground facilities.

On a log–log chart, Fig. 4, the K_{St} value is plotted against the surface area to volume ratio of explosion vessels for sulphide dusts Type I and Type II. A smaller vessel has a greater surface area to volume ratio. It is obvious that the K_{St} value increases with the size of explosion vessel. The K_{St} values from a 1 m³ vessel are the highest in the available experimental results and they

TABLE 2

Effect of vessel size on explosion parameters

Sample	Vessel size	P_{max} (MPa)	$(dP/dt)_{max}$ (MPa m/s)	Igniter	K_{St}	Reference
	1 m³	0.30	2.3	Detasheet (15 g)	2.3	[1]
Sulphide dust Type I	20 L	0.31	2.4	C.I.ᵃ (5 kJ)	0.65	[5]
		0.32	4.2	C.I. (10 kJ)	1.14	[5]
		0.30	1.1	C.I.	0.3	[4]
		0.32	0.8	C.I.	0.22	[6]
	8 L	0.36	3.7	Spark	0.74	[7]
Sulphide dust Type II	1 m³	0.37	4.69	Detasheet (15 g)	4.69	[1]
	20 L	0.40	8.3	C.I. (10 kJ)	2.25	[5]
	8 L	0.56	5.7	N.C.ᵇ (0.75 g)	1.14	[8]
	1 L	0.04	0.7	Spark	0.07	[2]
Bituminous coal (37% volatile)	1 m³	0.87	10.5	C.I. (10 kJ)	10.5	[9]
	20 L	0.77	12.1	C.I. (5 kJ)	3.3	[4]
	1 L	0.72	15.9	Spark	1.59	[11]

ᵃC.I. = Chemical Igniter.
ᵇN.C. = Nitrocellulose.
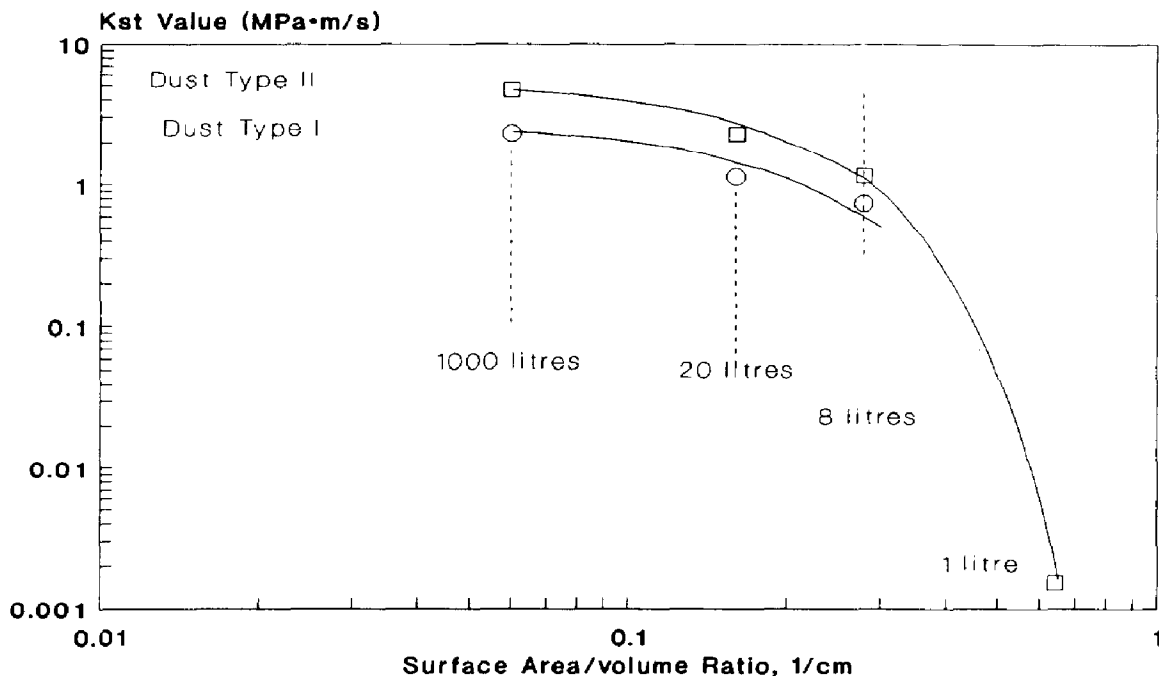
Kst Value (MPa·m/s)

Fig. 4. Scaling of sulphide dust explosions.

seem to be close to a maximum. However, it is not certain whether the 1 m^3 chamber reaches the minimum size to generate constant K_{St} values. Further investigation is required to clarify this point although the application of K_{St} values to dust explosions in mine entries might be debatable because of the effects of turbulence [9,10].

To accurately evaluate the K_{St} value of sulphide dusts the exact same dust sample needs to be tested in different vessel sizes with the same type of ignition source. The igniter must have enough strength to enable the dust cloud to explode in different vessels. Thus the standardization of igniters seems necessary not only for explosion scaling but also for general research in this field.

Electrical sparks should no longer be used because they are not reliable when igniting a sulphide dust cloud [12]. Chemical igniters, such as the Sobbe igniters [13], could be used in small vessels as long as "overdriving" does not occur. According to the results from 20-litre and 10.3 m^3 experiments [12,14], it seems that higher strength igniters are required for larger vessels. With volume larger than 1 m^3, a chemical igniter may not be strong enough. The ignition and reaction of the chemical igniter may take a relatively long time compared to the time of the explosion pressure rise in a sulphide dust explosion. Since the ignition energy is delivered over a time period, not all of the energy in the chemical igniter contributes to the dust ignition. To examine this, 20 g black powder was used to ignite sulphide dust Type I in the 1 m^3 chamber. The explosion pressure was found to be much lower than when the

same dust was ignited by Detasheet. A large portion of non-reacted dust was found in the explosion residual. It is believed that this part of the dust had fallen on the floor before the dust explosion occurred because of the slow combustion rate of the black powder and the slow rate of energy release. It appears that explosive igniters, such as detonators and high explosives, are suitable for the ignition of sulphide dusts in large explosion vessels (e.g. $> 1 \text{ m}^3$). For this reason and in order to simulate the actual ignition source in underground sulphide mines explosives were used in the present study.

Another important factor is the high specific gravity of sulphide dusts (sulphide dust is about three times heavier than carbonaceous dusts) which makes the suspension time much shorter if the same degree of turbulence is created. Thus the igniter's energy delivery time is required to be shorter meaning that faster burning igniters should be used for the heavy sulphide dusts.

In the hazard rating system (St-class) [3] based on K_{St} values, the combustible dusts encountered in the mining industry fall into the St-1 class. For example, the bituminous coal dust, which is the most reactive and energetic material among mining dusts, has a K_{St} value about 10.0 MPa m/s, while the value is lower for oil shale and sulphide dusts. Since this range, $K_{St} < 10.0$ MPa m/s, falls in the lower portion of the St-1 class, there is no apparent difference between these materials in terms of hazard classification. Furthermore most of the commonly encountered dusts fall into the St-1 class, since Bartknecht's St-0 to St-3 classification [3] covers a wide range of K_{St} values. Very few dust materials reach the St-3 class. To be able to classify the majority of dusts, particularly those encountered in the mining industry, a finer classification seems to be necessary for the K_{St} values ranging from 0 to 20.0 MPa m/s. For instance, the classification could be divided as follows:

Weak: $K_{St} = 0$–5.0 MPa m/s;

Moderate: $K_{St} = 5.0$–10.0 MPa m/s;

Strong: $K_{St} = 10.0$–20.0 MPa m/s.

In this case, most sulphide dusts fall in the weak range, whereas coal dust lies on the border line between moderate and strong. Protective measures can then be designed for each class.

5. The explosion limits

For a dust explosion to occur, the dust concentration must fall into the range between a Lower Explosion Limit (LEL) and an Upper Explosion Limit (UEL). With dust concentrations lower than LEL or higher then UEL, the dust clouds cannot explode with self-sustained flame propagation although part of the dust

(adjacent to the ignition source) might be ignited. The lower explosion limit is of practical importance in the control and prevention of dust explosions.

For sulphide dusts the LEL was found to vary with the strength of the ignition source. Figure 5 shows the result obtained when Detasheet was used to ignite the sulphide dust Type I. It follows that the lower explosion limit for the dust depends on the weight of the explosive charge used. As indicated in the figure, the minimum weight of Detasheet to ignite the dust is 6 g and the lower explosion limit is about 300 g/m^3 for sulphide dust Type I. This limit is expected to vary with the sulphur content of the sulphide dust. In general, a dust with higher sulphur content should have a lower LEL value, and vice versa.

The UEL is of limited practical interest in the case of dust explosions. For sulphide dust Type I, an explosion did not occur for a concentration of 2500 g/m^3 with 15 g Detasheet as the igniter, while an explosion did occur at a concentration of 2000 g/m^3 with the same igniter.

It is worth mentioning that between LEL and UEL, there is an optimum dust concentration below or above which the explosion pressure will decrease. The experimental results are shown in Fig. 6. For sulphide dust Type I the concentration for maximum explosibility was found to be about 1000 g/m^3. This is higher than the stoichiometric concentration. It is worth noting that with reduced dust concentration, both explosion pressure and the rate of pressure rise decrease more rapidly than with increased dust concentration.
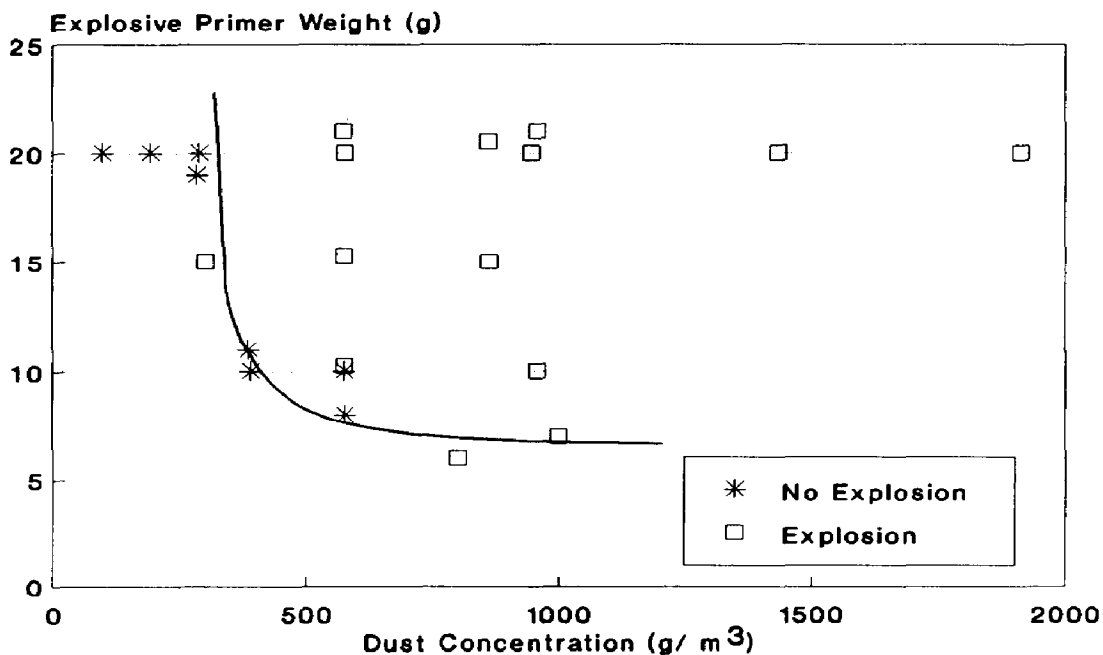

Fig. 5. Lower explosion limit and minimum igniting weight of Detasheet for sulphide dust Type I.
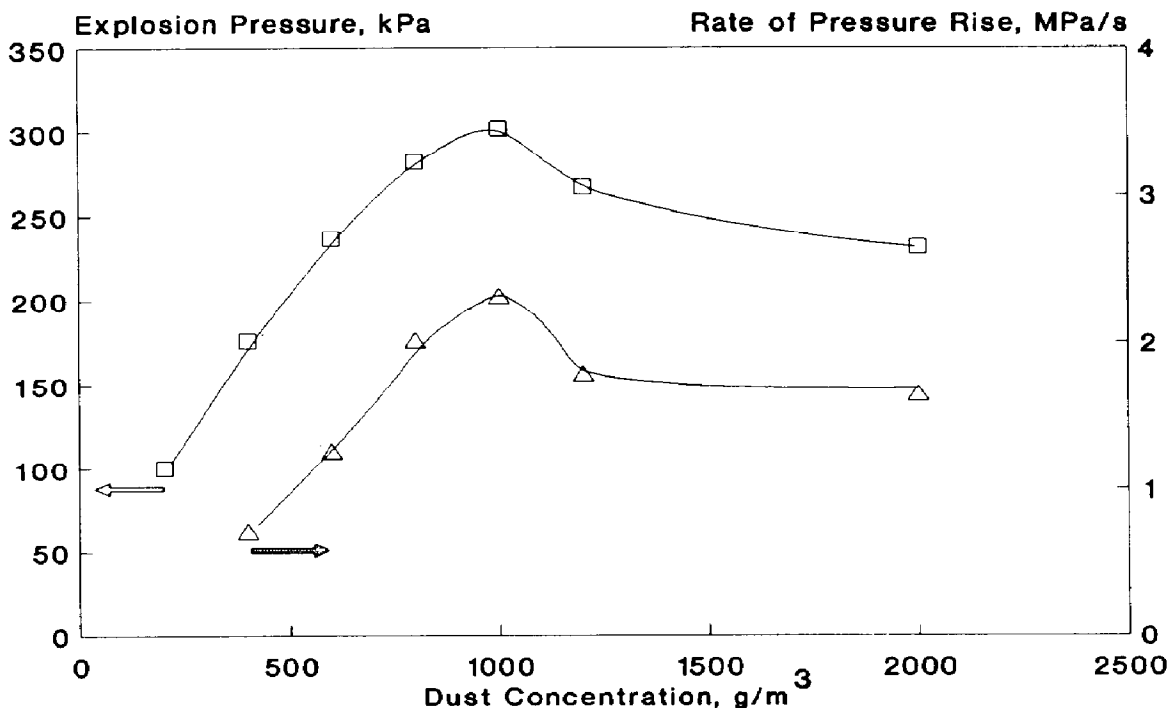
Fig. 6. Effect of dust concentration on peak explosion pressure and maximum rate of pressure rise.

6. Ignition criterion of sulphide dusts by explosives

From the investigation of the key explosives properties which influence the ignition of a sulphide dust cloud, it has been found [15] that the secondary explosion of detonation products is the dominant factor causing dust ignitions when using aluminized explosives or high explosives with very negative oxygen balances. With non-aluminized mining explosives such as ANFO (ammonium nitrate–fuel oil) and emulsion explosives, the temperature of explosion is the key factor in choosing an explosive for underground mine blasting.

A variety of explosives have been used to ignite the sulphide dust Type I at the same dust concentration (1000 g/m^3). The tests involved three ANFO explosives and four emulsions prepared on site to vary the oxygen balance level, as well as one commercial emulsion explosive and two low density emulsion explosives. The minimum weight of these explosives to ignite the sulphide dust cloud is listed in Table 3.

Table 4 provides the theoretical parameters of these explosives. The calculation was carried out by using a computer code, TIGER, which is a thermohydrodynamic computer code to calculate explosives detonation properties [16,17].

TABLE 3

Minimum explosive weight to ignite the sulphide dust cloud

Explosive	Weight (g)
ANFO #1 (OB^a = 89.4)	130
ANFO #2 (OB = −17.1)	96
ANFO #3 (OB = −123.6)	130
Commercial emulsion	130
Emulsion #1 (OB = 48.4)	158
Emulsion #2 (OB = −4.5)	135
Emulsion #3 (OB = −27.2)	130
Emulsion #4 (OB = −102.8)	135
Low density emulsion A (ρ = 1.2 g/cm^3)	150
Low density emulsion B (ρ = 0.75 g/cm^3)	180

[a]OB–Oxygen Balance (g O_2/kg explosive).

TABLE 4

Calculated explosive parameters[a]

Explosive	ρ (g/cm^3)	OB	VOD	P_e	T_e	Q_e	E_{ign}
ANFO #1	0.85	89.4	4480	1.87	1968	2.67	348
ANFO #2	0.85	−17.1	4890	2.25	2398	3.64	350
ANFO #3	0.85	−123.6	4980	2.33	2129	3.23	420
Emulsion #1	1.0	48.4	4540	2.14	1618	2.11	334
Emulsion #2	1.0	−4.5	4810	2.45	1868	2.66	359
Emulsion #3	1.0	−27.2	4850	2.48	1810	2.57	335
Emulsion #4	1.0	−102.8	4910	2.53	1714	2.45	331
Commercial emulsion	1.15	−0.7	5510	3.55	1888	2.83	367
Low density emulsion A	1.20	10.8	5443	3.49	1678	2.42	362
Low density emulsion B	0.75	9.9	3407	0.93	1777	2.20	396

[a]Legend: *OB*–oxygen balance (g of oxygen per kg of explosive); *VOD*–velocity of detonation (m/s); P_e–explosion state pressure (GPa); T_e–explosion state temperature (K); Q_e–heat of explosion (kJ/g of explosive); and E_{ign}–minimum ignition energy of the sulphide dust cloud, kJ.

The minimum energy of ignition was calculated from the minimum weight of ignition multiplied by the heat of explosion at the thermochemical state.

It can be observed that the ignition can be explained by the explosion state temperatures for the ANFO and emulsion explosives with the exception of the low density emulsion (density equal to 0.75 g/cm^3). To ignite a sulphide dust
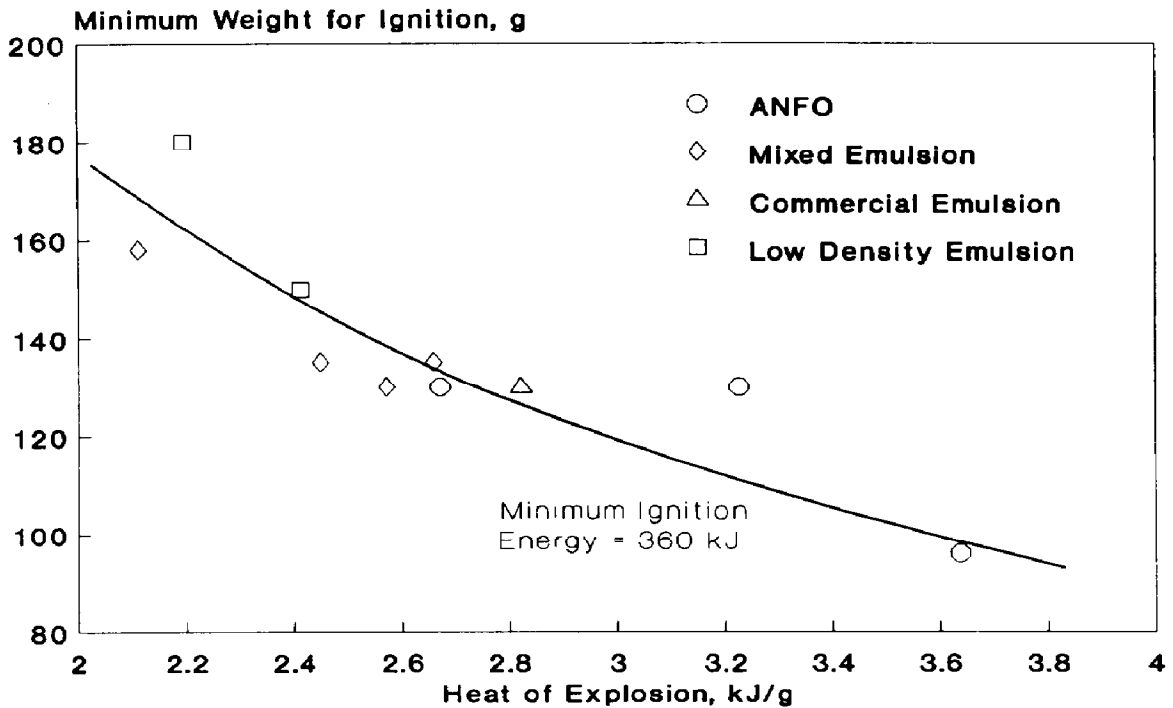
Fig. 7. Minimum ignition energy for sulphide dust Type I ignited by non-aluminized commercial explosives.

cloud, the minimum weight of explosive charge was found to decrease with the increase of explosion temperature. Without the low density emulsion, this trend agreed with the experimental results for the explosives at normal densities. However, the trend was reversed for the case of the low density emulsion explosive. Thus the minimum weight of explosive for a sulphide dust ignition cannot be explained by the explosion temperature alone.

If the minimum ignition weight is plotted versus the heat of explosion, Fig. 7, the general trend agrees well with all the non-aluminized mining explosives tested. In general, less weight is required to ignite a dust cloud with an explosive having a greater heat of explosion. This trend suggests an energy criterion for the ignition of the sulphide dust clouds. The regression line of Fig. 7 can be expressed by the following formula:

$$W_{ign} = \frac{E_{ign}}{Q_e} \qquad (3)$$

where W_{ign} is the minimum ignition weight of an explosive, g; Q_e is the heat of explosion at thermo-chemical state, kJ/g; E_{ign} is the minimum ignition energy for a particular dust, e.g. $E_{ign} = 360$ kJ for the sulphide dust Type I. The deviation of the regression is 5.84% for sulphide dust Type I.

7. Conclusions

The severity of sulphide dust explosions was examined using a $1 \, m^3$ explosion chamber and was found to be less violent than carbonaceous dusts such as wheat flour. The K_{St} value ranges from 1.2 to 2.3 MPa m/s for a sulphide dust Type I and from 3.5 to 7.0 MPa m/s for dust Type II. Scaling of the explosion hazard indicates that the K_{St} value increases with the size of explosion container, and $1 \, m^3$ seems to be close to the minimum size which produces constant K_{St} values for sulphide dust explosions.

For sulphide dust Type I, the lower explosion limit was found to be 300 g/m³ while the upper explosion limit was between 2000 and 2500 g/m³. The optimum concentration is about 1000 g/m³ which gives the maximum explosion pressure and rate of pressure rise. With non-aluminized mining explosives as the ignition source, the product of the heat of explosion of the explosive and the minimum weight of explosive for a dust ignition is approximately constant suggesting that it represents a minimum ignition energy criterion.

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