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Ignitions of explosive dust clouds by smouldering and flaming agglomerates

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Abstract

Surveys show that burning nests of dusts have been ignition source for dust clouds involved in industrial explosions. The literature indicates, however, that hot nests are a poor ignition source and are difficult to convey through powder handling plant. This paper describes some test in which clouds of dusts with a range of Minimum Ignition Temperatures (MITs) were dispersed around dust agglomerations smouldering and flaming at various temperatures. Smouldering nests of dusts prove to be poor ignition sources for most dust clouds, failing to ignite dusts even when there is a large difference between the nest temperature and the MIT of the dust cloud. Smouldering nests with temperatures above approximately 700–800 °C were, however, able to ignite sulphur clouds. Flaming nests, on the other hand, were able to ignite clouds of dusts up to the maximum MIT used, 600–675 °C.

Keywords: Dust explosion; Agglomerates; Ignitions

1. Introduction

Surveys of industrial dust explosion incidents show that, in a substantial percentage, friction and mechanical failure and flames and flaming material are known ignition sources. Surveys for the UK (Abbott, 1985; Porter, 1989) covering 1979–1988, and reviewing 303 events, showed friction and mechanical failure to be the reason for ignition in 18% of these incidents, and flames and flaming material to be responsible in another 15%. Overheating and spontaneous heating featured in a further 17%. Similarly, a survey by the Berufsgenossenschaftliches Institut fur Arbeitssicherheit (BIA) (Jeske and Beck, 1989) showed mechanical causes to be the most frequent source of ignition, with smouldering nests the second most frequent. The relevant percentages from the BIA survey were 26% for mechanical sparks, 11% for smouldering nests and 9% for mechanical heating.

Hazardous mechanical friction in dust handling plant is usually accidental: misalignment of components as in fans, mixers or mills, the presence of material trapped in conveying equipment. Although there has been a great deal of work done on the potential for ignition by the effects of mechanical sparks and frictional heating, there is no generally accepted method of estimating the likelihood of ignition from mechanical sources in relation to dusts. The information available in the literature is not sufficiently wide to give a guidance framework that would have wide use.

Hot surfaces are capable, if the temperature is sufficiently high, of igniting surrounding dust accumulations. The layer ignition temperature is measured in a standard test for a depth of 5 mm (ISSA, 1998), but because of the insulating effect of dusts, thicker deposits can ignite at lower temperatures (Testing methods for electrical apparatus installed in a dusty environment with a potential risk of explosion, 2001). The practical dangers are that a smouldering or burning layer can act either directly as an ignition source for a dust cloud or by means of agglomerations or nests of burning material that break away from deposits and ignite a dust cloud in another part of the plant.

Although explosion incidents are attributed to ignitions by nests of burning dust, it has been difficult experimentally to produce long-lasting, coherent clumps of smouldering powder that can travel through a powder handling plant (Pinkwasser, 1985). In addition, the literature indicates that nests are a relatively poor ignition source and only if they either break up in flight or hit the

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floor does the risk of an ignition substantially increase (Zockoll, 1989; Alfert et al., 1988).

The risk of an explosion due to hot nests encountering a dust cloud has been studied in this project. Burning nests with different characteristics have been introduced into clouds of dusts covering a range of Minimum Ignition Temperatures (MITs). Dusts with different Train Firing properties have been used as the nest material and the dust clouds have MIT values of approximately 400, 500 and 600 °C.

2. Literature review

Harper, Plain and Gibson (1997) have discussed the burning behaviour of powder accumulations on hot surfaces. The stages of ignition and the form of the combustion zone can be complex. Some powders burn directly in the solid phase either with a flame or by smouldering, others melt and burn as a liquid, whilst some burn with a large amount of flame. Some dusts can evolve large amounts of flammable gas when subjected to heat. A change from solid to liquid or agglomeration/expansion of dust particles to give an extended mass of material can block burning if diffusion of oxygen to the seat of burning is prevented.

A measure of the ignitability of a dust layer and intensity of burning of a dust layer is the Combustion Class (CC) (ISSA, 1998). This classification is based on the behaviour of a defined dust heap when subjected to a gas flame or hot platinum wire:

1. CC1: No ignition; no self-sustained combustion
2. CC2: Short ignition and quick extinguishing; local combustion of short duration
3. CC3: Local burning or glowing without spreading; local sustained combustion but no propagation
4. CC4: Spreading of a glowing fire; propagation smouldering combustion
5. CC5: Spreading of an open fire; propagating open flame
6. CC6: Explosible burning; explosive combustion.

The train firing test assesses flammability with reference to different ignition sources, and the Combustion Class is allotted based on the result. Not all dusts have the ability to form a coherent burning nest.

Once a smouldering or burning deposit has developed, nests, ranging in size from several millimetres to several centimetres, may break off and, carried along by an air stream until they reach an extensive dust cloud, then act as an ignition source.

However, the train firing test does not, at first sight, give an indication of the likelihood that a burning nest will form. The powder or dust needs to coagulate and any accumulations that detach need to travel for some distance as a unit. Furthermore, combustion behaviour in plant with flowing air will be different to when the air is stationary, as Zockoll (1989) has shown.

At present, however, it is unclear which properties of a dust nest make it an effective ignition source. Despite all the reports of ignition incidents in industrial plant, experimental studies have in the main indicated that ignition of dust clouds by hot nests is not easy. Pinkwasser (1985) showed that smouldering material entering a pneumatic conveying line was soon extinguished—the distance to extinguishment depending on the dust concentration.

Pinkwasser used an 80 m length of 100/110 mm i.d. pipe, with six 90° elbows, which ended in a cyclone. Nests of smouldering material were introduced through an air-lock at the end of the pipe remote from the cyclone. The powder conveying rate was measured from the weight of powder introduced into a known volume of conveying air over a given time, and the mean powder concentration calculated. The temperature of the smouldering material was measured by thermocouples, and the distance of travel of the smouldering material by spark detectors and flame detectors. The powders examined were three grades of flour, with K_{st}-values below 100 bar m s^{-1}, and CC ratings of 5.

Only one of the powders was capable of producing smouldering nests. The powder properties were: moisture content 8.9%, bulk density 290 kg/m^3, median particle size 120 microns and minimum ignition energy approximately 100 mJ. A much coarser-grained flour with a bulk density of 510 kg/m^3 failed to produce nests, as did a finer grained flour with the properties: moisture content 13.1%, bulk density 440 kg/m^3, median particle size 55 microns and minimum ignition energy approximately 500 mJ.

Glowing clumps up to 15 mm diameter, with temperatures of 500–550 °C, were fed into the line. In dust-free air, glowing particles were transported, in conveying velocities of 10 and 20 m/s, as far as 68 m. But as the powder loading in the airstream increased the distance to extinction of nests of approximately 10 g decreased substantially. Extinction was promoted by breaking up of a smouldering nest into individual glowing particles. No dust explosions were detected when powder-loading was within the explosive range.

Pinkwasser (1986) concluded that it was impossible, with the dusts tested, for smouldering nests of approximately 10 g weight to be conveyed in a powder loading of greater than 1 kg/m^3 of air, but that in conditions where powder loading is low–exhaust systems and under startup–smouldering material could be conveyed over relatively long distances.

Alfert et al. (1988) used a pneumatic transport system ending in a 5.8 m^3 filter unit. At an air speed of 35 m/s, only very strong nests could be transported. Charcoal nests of 50 cm^3 volume entered the filter only as small agglomerations (< 1 cm^3) even after a relatively short distance (11 m), and with maize starch as the explosive atmosphere in the filter even large nests (0.5 litre) produced no ignitions in the system. When fine wood dust was used to give the explosive atmosphere, ignition occurred in the filter, but not in the pipeline.

Pinkwasser (1986) showed those smouldering nests with a temperature of 700 °C, free-falling into dust clouds, did not produce an ignition in explosive atmospheres of wheat flour or wheat starch. Only when nests of at least 25 mm diameter and weight of at least 15 g landed on the bottom of the 1 m tall test column did some ignitions occur. Jaeger (1989) found that smouldering nests could be produced only with dusts having a Combustion Class greater than 3. A minimum nest area of 75 cm^2 and surface temperature of 900 °C were required for igniting clouds of dust with Minimum Igniting Temperatures less than 600 °C. Alfert et al. (1988) noted that nests of low mechanical strength disintegrated during a fall and generated a large fireball that acted as an ignition source. Mechanically stable nests were capable of igniting the cloud only when they reached the silo floor, but could get covered with dust before an explosion had time to start. In these tests, nests of known size were dropped through dust free air in a silo with a height of 22 m. The dusts were charcoal, cork dust and wood dust. Charcoal has a strong nesting structure; no burning of the charcoal particles occurred, and when the nest reached the floor of the silo, a shower of glowing particles was produced. Cork dust forms stable nests; flaring up of the nests was noted at approximately half the height of the silo, and on the silo floor. Wood dust produces unstable nests; these could break up in the very top part of the silo creating a fireball, remain intact and flare up in the upper half of the silo or reach the floor and flare up on impact or not at all.

When nests were dropped into an explosive atmosphere of maize starch, nests of wood dust with a size of 0.5–1 litre produced no ignition in 40% of the tests. Nest with volumes of 1–1.5 litres ignited equally in the upper part of the silo or on the floor. Nests of cork dust produced no ignitions, but could start fires in settled maize starch powder. Charcoal nests could produce ignitions if they were mechanically broken up, and also a short time after reaching the floor.

Zokoll (1989) has reported some tests using milk powders as both the nest material and the explosive dust cloud. Initial tests in which both dust and smouldering nest were dropped into the test chamber simultaneously showed that fist-sized nests at temperatures approximately 100 °C or more above bulk powder Minimum Ignition Temperature as measured in the BAM furnace test did not ignite ground corn and milk powder clouds. Ignitions did not occur even when the nests, while falling, were broken up by blades. Ignition of dust clouds could not be achieved with nests that did not burn but had internal temperatures of 700–800 °C. Nests at 1200 °C did ignite the dust clouds but only after impact on the floor of the explosion vessel. When dust was dropped over smouldering nests on the vessel floor, cloud explosions could occur at temperatures of about 860 °C. A flaming nest could, however, be practically extinguished by the dispersal of milk powder around it in the explosion vessel. Tests on the development of smouldering in nests under the influence of a 0.5m s^{-1} air stream showed that smouldering developed differently depending on the type of milk powder. At higher air speeds open fires occurred in relatively large quantities of skimmed milk powder. At air speeds of about 10 m/s compact smouldering nests reached temperatures of 1200 °C in the hottest spots. The transition from smouldering into open fire occurs around 800–850 °C, depending on the type of milk.

Work by Bailey and Walker at Syngenta (Bailey & Walker, 2000) has shown that clouds can be ignited by various burning or smouldering ignition sources. Three ignition sources—paraformaldehyde, which burns with a flame, Fe^{3+} (H_2), which smoulders, and incandescent particles of sawdust—were used. Sulphur and lycopodium dust clouds of various concentrations were blown over the first two of the ignition sources, and both dusts ignited. The incandescent particles were introduced into the dust clouds soon after the clouds had been produced. The sulphur clouds ignited, but the lycopodium did not.

These tests were repeated with dusts of various MIT values, from 270 °C to above 1000 °C, as measured in the Godbert Greenwald furnace. With the burning layer, dusts with MITs above 600–800 °C did not ignite; with the smouldering layer, dusts with MITs above 340 °C, approximately, did not ignite; with the incandescent particles, dusts with MITs above about 330 °C did not ignite. Some tests using layer ignition sources of various areas and temperatures showed that as the area decreased, for a given temperature, the dust MIT above which a dust cloud did not ignite increased.

In summary, the likelihood of ignition of a dust cloud by a hot nest depends on the temperature of the nest, its residence time in the dust cloud and the availability of oxygen to the burning area. Griesche and Brandt (1976) have shown that the Minimum Ignition Temperature of a dust-cloud decreases substantially when the residence-time of a dust in a Godbert-Greenwald furnace increases. The longer a local part of a dust cloud remains in contact with a smouldering nest, the more likely it is that an ignition will occur. It appears, also, that dust clouds can extinguish burning nests and an ignition be prevented, if conditions are right.

3. Experimental

A vertical tube apparatus was built, consisting of a 2 m long perspex tube with an internal diameter of 0.3 m. A vibrating hopper and screw feed arrangement was designed to feed dust into an air flow in a pipe connected to the top of the tube. The rate of feed and air flow were both variable so that a wide range of dust concentrations could be produced (see Fig. 1).

The burning behaviour of a range of dusts was tested by subjecting a line of each dust to a flame ignition source. From the results several dusts was selected with characteristics covering a range of cloud Minimum Ignition Temperatures and Layer Ignition temperature values. The ignitability characteristics for the dusts selected are shown in Table 1.

For the main series of tests, coherent smouldering or burning nests were to be used as the ignition source in the vertical tube arrangement. In order to obtain sustained combustion some form of airflow either through or over the smouldering dust sample is usually necessary. Several different methods for producing sustained combustion were tried and the best was a bank of dust over which was passed warm air at 50 °C. This method allowed sustainable smouldering nests to be created with most dusts. Land Cyclops Ti35+ infrared Thermal Imaging camera was used to measure the burning temperature of the various dusts.

The dusts were banked up in a 100 mm diameter tray as shown in Figs 2 and 3 and ignited using a blow torch.

Table 1
Ignitability characteristics[c]

Dust type	Dust layer glow temp (°C)	Minimum Ignition Temperature (MIT) (°C)
Sulphur	250–270	280–370
Lycopodium	280	410[a]
Woodflour	310–320	480–500[b]
Tea (Earl Grey)	300	510[a]
Cornflour (st2)	440–450	450–500[b]
Calcium stearate	>450	450–500[b]
Anthraquinone	>450	600–675[b]

[a] Measured in BAM oven at HSL
[b] Measured in Godbert Greenwald furnace at Syngenta
[c] Other results were taken from (Eckhoff, 1997)

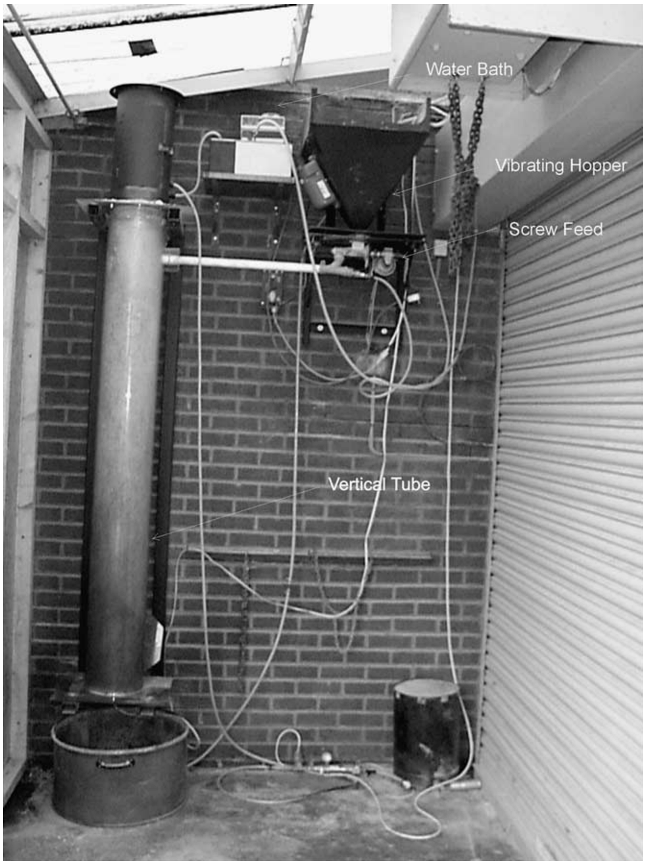

Fig. 1. Vertical tube apparatus.

Fig. 2. Baby milk powder burning nest, burning mode—smouldering.

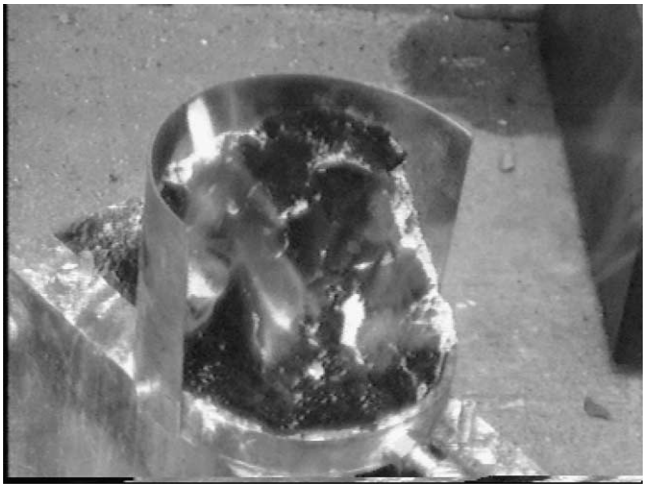

Fig. 3. Baby milk powder burning nest, burning mode—flame.

The burning temperatures of the agglomerates are listed in Table 2.

A burning nest of dust was positioned inside the vertical tube close to the bottom and its burning mode noted. A dust cloud was then created within the tube using the screw feed arrangement.

In some of the tests the burning nest was dispersed by an air blast from a conical nozzle buried in the dust, to see if the action of breaking-up the smouldering deposit would result in ignition of the dust cloud.

4. Results and discussion

An analysis of the results is shown in Table 3, where the temperatures of the nests are divided into three bands—approximately 700, 800–900 °C; and approximately 1000 °C and above. The type of burning is listed, along with the Minimum Ignition Temperature of the dust cloud and whether or not ignition occurred. In the majority of tests where smouldering was the mode of combustion, ignitions did not take place even when high smouldering temperatures were evident and the difference between this temperature and the cloud MIT was high. Only when the nest was dispersed and the temperature difference was high did ignition occur. Sulphur dust clouds were the only ones which would ignite on smouldering nests, but even then the temperature difference between the nest and the cloud MIT was greater than 500 °C. By contrast, if flaming combustion took place ignition of a dust cloud was practically guaranteed, even when the flames were small.

The results from the current project are in agreement with those of Bailey and Walker. In their tests, smouldering nests did not ignite dust clouds with MIT values above 400 °C, but flaming nests were able to ignite clouds of all the dusts used up to the maximum MIT used, 600–675 °C. Smouldering nests with a temperature above approximately 700–800 °C ignited sulphur clouds.

A review of the wider literature also shows that smouldering nests are poor sources of ignition. The likelihood of ignition of a dust cloud by a hot nest is low if the nest burns only by smouldering. Ignition depends crucially on the production of either flame or incandescent particles and if flaming does take place then the risk of an ignition is very high.

When it is considered that in order for a nest to ignite a dust cloud the following are needed: a dust capable of holding together as a nest; a means of heating this; a means of transporting it through the system, a means of breaking the nest open and producing flames or high temperatures, and a dust cloud with an explosible concentration at the right time, then the risks from glowing nests are probably overestimated and many events ascribed to them may have been caused some other way.

A more critical look at actual incidents, including in particular the nest forming properties of dusts where nests have been blamed for the incident, might well lead to a revision of the previously assigned causes of ignition.

In practical situations, a test similar to the Train Firing Test is a useful method for determining whether a dust deposit will either propagate smouldering or produce flame, although both the temperature and airflow inside dust-handling plant can have an effect on the burning behaviour. If the air above the dust deposit is at a temperature higher than normal room temperature, the possibility for ignition of a dust cloud may rise.

Table 2
Burning temperature of dust deposits

Dust tested	Type of burning	Air applied at 50 °C?	Temperature range (°C)
Wood	Smouldering	No	690
Wood	With flame	No	730
Wood	Smouldering	Yes	850–900
Earl Grey fines	Smouldering	Yes	800–940
Lycopodium	With flame	No	650
Lycopodium	With flame	Yes	1056–1173
Lycopodium	With flame	After air removed	820–850
Lycopodium	Smouldering	Yes	1050
Baby milk powder	Smouldering	Yes	950–1000
Baby milk powder	Smouldering	No	700
Baby milk powder	With flame	Yes	960
Cornflour (St2)	Smouldering	No	800
Cornflour (St2)	Small pockets of flame	Yes	830
Cornflour (St2)	With flame	Yes	900
Coal dust	Smouldering	Yes	>1170
Calcium stearate	With flame	Yes	700
Calcium stearate	With flame	No	900
Anthraquinone	With flame	No	860
Hot coil (used on setup tests)			670–680

Table 3
Ignition conditions

Temperature of Nest °C	Mode of Combustion	MIT of Dust Cloud (°C)	Ignition Y/N
Wood 690	Smoulder	280–370	N
Wood 690	Smoulder	480–500	N
Wood 690	Smoulder	410	N
Wood 690	Smoulder	600–675	N
Wood 730	Flames	410	Y
Wood 730	Flames	450–500	Y
Wood 730	Flames	600–675	Y
St 2 Cornflour 830	Flame	450–500	Y
Anthraquinone 860	Flame	600–675	Y
Tea 800–940	Smoulder	510	N
Wood 850–900	Smoulder	280–370	Y
Wood 850–900	Smoulder	410	N
Wood 850–900	Smoulder	450–500	N
Wood 850–900	Smoulder	480–500	N
Calcium Stearate 900	Flame	450–500	Y
Tea 800–940	Smoulder	600–675	N
Milk 950–1000	Smoulder	410	N
Milk 950–1000	Smouldering then dispersed	410	Y
Milk 960	Flame	410	Y
Lycopodium 1050	Smoulder	410	N
Coal>1170	Smoulder	410	N
Coal>1170	Flame	410	Y
Coal>1170	Smoulder	600–675	N
Coal>1170	Flame	600–675	Y

Various tests have been developed to measure the ignition behaviour of dust deposits in a stream of hot air. Similar tests could be used to tell whether smouldering dusts were in danger of flaming. The I.ChemE Guide, *Prevention of fires and explosions in dryers* described tests developed to simulate various conditions and obtain measurements of the temperature at which exothermic reaction begins (Abbot, 1990). If the dust deposits and surrounding conditions properly simulate practical situations, the temperature at which deposit burning progresses to flaming combustion could be used as a basis for safe procedures with an adequate safety margin incorporated.

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