Influence of initial and explosion-induced turbulence on dust explosions in large vented silo cells

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Abstract

The violence, or the rate, of a dust explosion is a deciding factor as to whether venting of the explosion will be effective. The turbulence of the dust cloud, initial as well as explosion-induced, plays a central role in determining the explosion violence. This was demonstrated in dust explosion experiments in large vented silo cells of 500 and 236 m³. In vented silo cells of $L/D > 6$, explosion-induced turbulence can increase the explosion violence substantially. Further development of mathematical models for simulation of dust explosions in silo cells and other process equipment should be encouraged.

Résumé

La violence, ou la force, d'une explosion de poussière est un facteur décisif pour savoir si oui non le percage de l'explosion peut être efficace. La turbulence du nuage de poussière, initiale et nourrie par l'explosion, joue un rôle clé dans la détermination de la violence de l'explosion. On a pu faire la démonstration de cela dans des explosions de poussière dans de grands silos aérés de 500 et de 236 m³. Dans les silos aérés de $L/D > 6$, la turbulence nourrie par l'explosion peut augmenter la violence de l'explosion de manière significative. Il faudrait encourager la mise en place de nouveaux modèles mathématiques destinés à la simulation des explosions de poussière dans des silos et d'autres équipements analogues.

Zusammenfassung

1. Introduction

Industrial enclosures, such as conventional process equipment, are normally too weak to withstand the pressures exerted even by only partly developed, confined dust explosions. Consequently a primary objective of fighting an explosion, after it has been initiated, is to prevent the building-up of destructive overpressures. Several techniques for preventing destructive overpressures are in current use in industry. Probably, the most widely used is venting.

Large storage silos of up to several thousand m³ volume are common in the grain, feed and flour industries. In order to protect the wall and roof of such silo cells against excessive internal overpressure in the case of a dust explosion inside the silo, the silos are often provided with an explosion vent in the top part, normally in the roof. However, the sizing of such vents remains a complex and partly controversial issue.

The rate of combustion of the dust cloud, i.e. the rate of heat generation inside the enclosure where the explosion is initiated, is a deciding factor as to whether a given vent design will perform adequately. In view of the fact that the combustion rates of dust clouds in industrial practice, even of the same dust, vary substantially, it is important to base the design of the vent arrangement on the best possible estimate of the combustion rate, or explosion violence, that will occur in practice.

2. Factors influencing the explosion of dust clouds

There are several important factors, and the comprehensive list may look as follows:
(a) Chemical composition of the dust, including its moisture content.
(b) Chemical composition, and initial pressure and temperature of the gas phase.
(c) Distributions of particle sizes and shapes in the dust, determining the specific surface area of the dust in the fully dispersed state.
(d) Degree of dispersion, or de-agglomeration, of dust particles, determining the effective specific surface area available to the combustion process in the dust cloud in the actual industrial situation.
(e) Distribution of dust concentration in the actual cloud.
(f) Distribution of initial turbulence in the actual cloud.
(g) Possibility of generation of explosion-induced turbulence in the still unburnt part of the cloud. (Location of ignition source important parameter. Flame jet ignition will create turbulence.)
(h) Possibility of flame front distortion by other mechanisms than turbulence.
(i) Possibility of significant radiative heat transfer (highly dependent on flame temperature, which in turn depends on particle chemistry).
Factors (a), (b), (c) and (i) can be regarded as basic parameters of the explosible dust cloud. Factors (d) to (h) are, however, influenced by the actual industrial dust cloud generation process and explosion development. These in turn depend on the nature of the industrial process (flow rates, etc.) and the geometry of the system in which the dust cloud burns.

In view of the wide spectrum of dust cloud concentrations, degrees of dust dispersion and turbulence, and locations of potential ignition sources in industry, a correspondingly wide spectrum of possible dust cloud combustion rates must be expected for any given dust.

This complex reality of the process industry is also shared by laboratory experimentation and represents a constant challenge in the design of adequate experiments and the interpretation of experimental results.

3. Role of turbulence in increasing the combustion rate of dust clouds

3.1. Initial and explosion-induced turbulence

In practical terms, turbulence may in the present context, be described as a state of rapid, more or less random, movement of small elements of the dust cloud relative to each other in three dimensions. If the cloud is burning, turbulence will give rise to mixing of the hot burnt and burning parts of the cloud with the cold unburnt parts, and the cloud will become a three-dimensional laminate of alternating hot/burning and cold unburnt zones. Therefore a turbulent cloud will burn much faster than a quiescent cloud through which a smooth, comparatively thin flame sheet is propagating.

In relation to dust explosions in industry two kinds of turbulence, differing by their origin, have to be considered. The first is turbulence generated by the industrial process in which the dust cloud is formed, whether an air jet mill, a mixer, a cyclone, a bag filter, a pneumatic transport pipe, or a bucket elevator. This kind of turbulence is often called initial turbulence. The second kind is generated by the explosion itself by expansion-induced flow of unburnt dust cloud ahead of the propagating flame. The level of turbulence generated in this way depends on the speed of the flow and the geometry of the system. Vent openings and obstacles, like the buckets in a bucket elevator leg, enhance the turbulence generation under such conditions.

In long ducts or galleries a positive feed-back loop can be established by which the flame can accelerate to very high speeds and even transit to a detonation.

Further details and references to published work are given by Eckhoff (1991).
3.2. Influence of initial turbulence on the violence of dust explosions in closed vessels.

The marked influence of initial turbulence on the combustion rate of a dust cloud is exposed clearly in dust explosion experiments in closed vessels, using transient dust clouds.

A series of such experiments were described by Eckhoff (1977). Lycopodium dust was dispersed into a cloud in the Hartmann bomb by a short blast of air. Ignition of the cloud was accomplished by an electric spark of a few J net energy, or by a 100 J chemical igniter, fired at a pre-set delay after onset of dust dispersion.

Some results are given in Fig. 1. The ignition delay is a relative measure of the initial turbulence. In the early stages of dust dispersion, the dust cloud was quite turbulent, but the turbulence faded away with time as the dispersion air flow diminished. Therefore, when explosion experiments with the same dust were repeated in the vessel, using different delays between initiation of dust dispersion, and ignition, the dust clouds had different levels of initial turbulence at the moment of ignition.

![Fig. 1. Influence of initial turbulence on the explosion rate of a dust cloud. Experiments with 420 g m⁻³ of lycopodium in air in the 1.2 l Hartmann bomb. 5 experiments per delay. Bars indicate ± 1 standard deviation. Note that ‘bar (g)’ denotes gauge pressure, i.e. pressure above atmospheric pressure. After Eckhoff (1977).]
As Fig. 1 shows, the explosion violence, in terms of the maximum gradient of pressure vs. time, decreased markedly, by at least an order of magnitude, as the initial turbulence faded away. However, the maximum explosion pressure remained fairly constant up to delays of about 200 ms. This is due to the fact that the maximum pressure is essentially a thermodynamic property, reflecting the total heat released in the combustion of the dust, whereas the rate of pressure rise contains a strong kinetic component. However, even the maximum pressure will start to decay when ignition delays become very long, due to settling-out of the dust, as is also indicated in Fig. 1.

The direct measurements of the rms (root mean square) turbulence intensity as a function of time after opening the dispersion air valve in a Hartmann bomb, by Amyotte and Pegg (1989), and their comparison of the data with the data from Hartmann bomb explosion experiments by themselves and Eckhoff (1977), give further evidence. The results are shown in Fig. 2. It is seen that a decay by a factor of almost ten of the turbulence intensity occurs within the same time frame from about 40 to 200 ms as a corresponding decay of \( \frac{dP}{dt} \) in Eckhoff's experiments in Fig. 1. It is also seen that the turbulence intensity increases systematically with the initial pressure in the dispersing air reservoir, i.e. with increasing strength of the air blast, in accordance with expectations.

Further discussion of these and similar experiments conducted by other workers is given by Eckhoff (1991).

4. The role of dust cloud turbulence in vented dust explosions

4.1. General outline

In the venting of dust explosions the pressure as a function of time \( P(t) \) in the vented enclosure is the net result of two competing processes:
- burning of the dust, causing heat production and hence pressure rise;
- discharge of unburnt cloud and combustion products through the vent opening, causing pressure decrease.

Therefore, the maximum explosion pressure in a given enclosure equipped with a given vent increases with the rate of burning of the dust cloud, or rate of heat release by combustion, in the enclosure. This not only implies that different dusts burn with different rates, but indeed also that the combustion rate of a given dust in a given enclosure can vary considerably, depending on the physical state of the cloud, in terms of dust concentration distribution, degree of dispersion or de-agglomeration of the particles, and last but not least, the turbulence level. In the present context the influence of turbulence is of primary interest.

It is to be expected in general that the maximum pressure in an explosion of a given dust in a given vented enclosure increases systematically with increasing turbulence level (e.g. expressed as an rms velocity) in the burning dust cloud. (At very high levels of turbulence, flame quenching phenomena may arise, but this aspect will not be considered here.)

4.2. Experiments by Tamanini and co-workers

The influence of dust cloud turbulence on explosion venting processes was studied specifically by Tamanini (1989). He and his co-workers conducted vented dust explosion experiments in a 64 m³ rectangular enclosure, the vent being a 5.6 m² square opening in one of the four 14 m² walls of the enclosure. Details of the experiments were given by Tamanini and Chaffee (1989).

The dust injection system consisted of four pressurized-air containers connected to 16 perforated dust dispersion nozzles. The dust was placed in four canisters, one for each of the pressurized air containers, located in the lines between the pressurized containers and the dispersion nozzles. On activation of high-speed valves, the pressurized air released from the containers entrained the dust and dispersed it into a cloud in the 64 m³ chamber via the 16 nozzles.

As discussed above for closed-vessel experiments, this dust dispersion method generates transient dust clouds characterized by a comparatively high turbulence intensity during the early stages of dust dispersion, and a subsequent marked fall-off of the turbulence intensity with increasing time from the start of the dispersion. This means that the turbulence level of such a dust cloud at the moment of ignition can be controlled by controlling the delay between start of dust dispersion and activation of the ignition source.

By varying the delay between onset of dust dispersion and ignition, Tamanini (1989) and Tamanini and Chaffee (1989) used this effect to study the influence of the turbulence intensity at the moment of ignition on the maximum pressure generated by explosion of a given dust at a given concentration in their 64 m³ vented chamber. The actual turbulence intensity in the large-
scale dust cloud at any given time was measured by a bi-directional fast-response gas velocity probe, in terms of the rms (root-mean-square) of the instantaneous velocity.

Figure 3 gives a set of data showing a clear correlation between the maximum pressure in the vented explosion and the average rms of the instantaneous fluctuating turbulence velocity at the moment of ignition, as measured by the pressure probes.

The contribution of Tamanini and co-workers is particularly valuable because it suggests that a quantitative link between systematic venting experiments, in which the initial turbulence is quantified, and real industrial explosion situations may be obtained via measurement of characteristic turbulence levels in dust clouds in industrial process equipment in which vented explosions may occur.

5. Influence of initial turbulence on violence of dust explosions in a 500 m³ vented silo of $L/D = 4$

The experiments to be reported were described in detail by Eckhoff and Fuhre (1984). The silo used is illustrated in Fig. 4. The dust was injected upwards into the silo through a 200 mm diameter pipe coinciding with the silo axis. In the final, destructive experiment, high initial turbulence was ensured in the upper part of the silo by maintaining turbulent injection of explosible dust cloud right through the entire explosion process.

The resulting pressure vs. time history is shown in Fig. 5. It consists of three phases. Following an initial small pressure rise of about 10 mbar after about 0.8 s, the onset of a "normal" rise of pressure ($\approx 0.17 \text{ bar s}^{-1}$) was observed at 1.3 s. The pressure continued to rise in this 'normal' manner up to about 55
Fig. 4. Cross section of 500 m³ steel plate silo used in the turbulent dust/air jet explosion experiment described by Eckhoff and Fuhre (1984).

Fig. 5. Pressure vs. time during explosion of clouds of maize starch in 500 m³ steel plate silo in the presence of a turbulent dust/air jet. 300 kg maize starch injected into the silo. 8.8 m² open vent in the silo roof. Ignition at the silo bottom. After Eckhoff and Fuhre (1984).
mbar at about 1.5 s. The overpressure developed at this point was right in the middle of the range of peak pressures obtained in the six preceding “normal” experiments (with initially quiescent maize starch clouds). However, at this moment the “abnormal”, very fast pressure rise began, resulting in a further pressure increase of more than 500 mbar in less than 0.2 s. The steepest part of this pressure rise phase had a slope of 14 bar s⁻¹, i.e. 80 times that in the “normal” phase. The maximum overpressure recorded before the silo ruptured was about 580 mbar. From the very high rate of pressure rise at the moment of rupture, it seems reasonable to deduce that had the silo been sufficiently strong to withstand the explosion, the pressure in the silo would probably have risen considerably higher than about 0.6 bar (g) before reaching its peak, in spite of the generous venting.

Figure 6 summarizes the results for the initially quiescent dust clouds (dust injection terminated a few seconds before ignition) and the single experiment with ignition while dust injection was maintained. The maximum explosion-pressure vs. vent-area relationship predicted by VDI 3673 (1979 edn.) is also included for comparison.

Figure 6 suggests that the combustion rate of a relatively quiescent dust cloud in a large empty vented silo of $L/D = 4$ is considerably lower than that implied in the VDI 3673 (1979 edn.) recommendations. However, the result from the experiment with high initial turbulence shows that not even these conservative recommendations constitute a universally valid worst-case. On the other hand, it can be argued that, as far as large silos are concerned, the

![Fig. 6. Comparison of experimental maximum explosion pressures from experiments in vented 500 m³ silo with and without initial turbulence, and predictions by VDI 3673 (1979 edn.). After Eckhoff and Fuhre (1984).](image-url)
dust cloud generation process illustrated in Fig. 4 is not likely to be representative of industrial practice.

6. Influence of explosion-induced turbulence on violence of dust explosions in a 236 m³ vented silo of $L/D=6$

These experiments were reported in detail by Eckhoff et al. (1987, 1988). A cross section of silo, indicating alternative dust injection and ignition points, and various diagnostics, is shown in Fig. 7.

In the case of Eckhoff et al. (1987) the vent was located in the silo roof, whereas in the experiments by Eckhoff et al. (1988) the vent opening was in the silo wall just below the top, the roof itself being fully closed. Dust was injected pneumatically into the silo either from the bottom or the top as indicated in Fig. 7. Air of the desired flow rate was supplied by a Roots blower, and

Fig. 7. 236 m³ silo in Norway for dust explosion experiments, with provisions for roof venting. $L/D=6$. After Eckhoff et al. (1987).
dust was fed into the air flow at the desired mass flow rate. Before ignition the air flow was stopped and the dust cloud allowed to calm down for a few seconds. Therefore, the initial turbulence of the dust cloud at the moment of ignition was negligible.

Figure 8 shows the influence of the location of the ignition point along the silo axis, on the maximum explosion pressure in the vented silo for three different vent configurations. Some influence of the vent configuration was observed. However, the main message of Fig. 8 is that there is a very marked increase of the maximum explosion pressure in the silo, from the order of 0.01 to the order of 1.0 bar (g), when the ignition point is shifted downwards in the silo from the top to the bottom. Some of this effect is due to different vented gas densities. In the case of top ignition the vented gas was essentially hot, low-density combustion products, whereas cold, high density dust cloud was vented during the first decisive phase with bottom ignition. This effect was studied theoretically by Nagy and Verakis (1983).

However, with bottom ignition the upwards flame front speed close to the vent exceeded 100 m s⁻¹ and there is little doubt that explosion-induced turbulence also played a central role. Thus quite early in this century, gas explosion experiments in one-end-open pipes had shown that as the explosion propagated along the pipe, it could undergo a dramatic change from harmless laminar flames, via a wide spectrum of turbulent combustion, to detonation. The secret of the dramatic flame acceleration was also resolved on a qualitative basis. After ignition, the first combustion phase occurs rather slowly as an approximately laminar flame spread. However, as a result of the heat produced by the combustion, the combustion products expand, and this leads to the still un-

![Fig. 8. Influence of location of ignition point in a 236 m³ vented silo of L/D = 6, on the maximum explosion pressure in the silo. Maize starch of 11% moisture and concentration ∼ 400-500 g m⁻³. After Eckhoff et al. (1987, 1988).](image-url)
burnt gas ahead of the flame being pushed towards the open end of the pipe. Depending on pipe diameter, flow rate, and the roughness of the pipe walls, the flowing unburnt gas will be rendered more or less turbulent. When the combustion zone approaches these turbulent regions further along the pipe, the combustion rate will increase. This leads in turn to faster expansion of the burnt gas, which in its turn increases yet further the flow rate of the unburnt gas ahead of the flame, and so on. In other words, there is a self-accelerating explosion process, or a positive feed-back loop, with the generation of flow-induced turbulence in the gas ahead of the flame as a key element.

Extensive experimentation in several countries with coal dust explosions in long pipes, ducts and large-scale galleries has confirmed that this rather multifarious picture indeed also applies to dust explosions, and explains why the location of the ignition point with respect to the vent was of such crucial importance for the pressure build-up during dust explosions in the 236 m³ silo. If ignition occurs at the silo top, close to the vent, there is no possibility of generating high-velocity flow and high turbulence levels in the unburnt cloud further down. These aspects were discussed in greater detail by Eckhoff (1987).

Figure 8 shows that a 4.4 m² wall vent in fact gave somewhat lower explosion pressures than a larger 5.7 m² vent in the silo roof. A possible explanation of this result was given by Eckhoff et al. (1988).

7. Initiation of dust explosions in large silo cells by strong flame jets

Alfert and Fuhre (1992) showed that flame jet ignition of dust clouds in a generously vented 2 m³ vessel gave rise to much higher maximum pressures in the vessel than those expected from even quite conservative venting guidelines. In principle a similar effect should be expected if a dust cloud in a silo cell is ignited by a flame jet.

As pointed out by Eckhoff (1987), analyses of accidental dust explosions involving silos indicate that most often the silo explosion is a secondary event, following a primary explosion elsewhere in the plant. For this reason, flame jets entering the silo from the outside through available openings seem to be a likely type of ignition source for silo explosions. In view of Fig. 8, however, it is crucial whether flame jet ignition takes place near the bottom of the silo cell or near the vented top.

7.1. Is flame jet ignition in the bottom part of the silo cell a credible event?

It has been suggested that some silo explosions in the past may have been initiated by a flame jet from a violent explosion below the silo that entered the silo through the discharge spout at the bottom. This suggestion implies first that the discharge spout is open, or can be blown open by an explosion below
the silo. Secondly, it implies that the explosible dust cloud in the silo is large enough to generate a significant explosion pressure. An initially open discharge spout would normally imply that the silo is empty, apart from dust layers on the wall and roof. If the dust cloud is to be generated from such layers, it must be dispersed either by mechanical vibrations or by an air blast preceding the flame jet.

The scenario that the silo spout at the bottom is open at the same time as the silo is being filled from the top seems rather unlikely for normal operational reasons. One could in theory envisage a situation where a dust explosion propagated in the tunnel below the silo at the same time as filling of the silo with dust from the top had just started with the bottom spout left open by mistake. In such a case, strong worst-case explosions could occur that no normal silo would be able to withstand, even if generous venting was provided. However, one must consider whether an accidental coincidence of the three events necessary to create this situation would be credible.

Whether or not it is likely that a closed bottom spout can be blown open by an overpressure from below also needs to be considered. In addition to blowing the spout open, the overpressure must also be able to lift any bulk material stored in the silo.

Another mechanism for generating and igniting dust clouds in silos from below could be that a dust explosion in the tunnel generates and compresses a dust cloud ahead of the flame, so that an unburnt explosible dust cloud at a higher than atmospheric pressure is pushed into the silo through any open bottom spout, and subsequently ignited inside the silo by the flame jet that follows it. If the size of the spout opening and the pressure drop across it are known, the amount of dust cloud entering the silo per unit time can be estimated. However, it does not seem obvious that large volumes of unburnt cloud can be generated in the silo in this way before the flame reaches the spout.

A more likely situation would be that the dust cloud was generated in the empty silo by dispersion of dust layers on the internal surface of the wall and roof. Dispersion of a 1 mm layer of grain dust on the internal wall of a 7 m diameter silo would give an average dust concentration of about 300 g/m$^3$ in the silo. Dispersion of such dust layers could be due to mechanical shaking caused by preceding explosions elsewhere in the plant. If an explosion had first occurred in the tunnel below the silo, ignition at the silo bottom could be accomplished by a flame jet entering the silo through the open bottom spout.

7.2. Flame jet ignition in the top part of the silo cell seems more credible

It is nevertheless felt that the most likely scenario for flame jet ignition in a large silo is a jet entering the silo in the top region, either through a dust extraction opening or through the product feeding system. This is likely both because these openings would be open during dust filling, and because the or-
Origin of dust explosions in grain elevators and feed and flour mills is often either the milling and grinding system or mechanical transport units such as bucket elevators.

As shown in Fig. 8, top ignition in a large slim silo, provided with a reasonable size vent at the top, only generates very low explosion pressures, of the order of a few tens of millibars, even with a large, effective ignition source, and with the entire silo filled with a worst-case concentration dust cloud. Flame jet ignition near the silo top would be expected to give somewhat higher, but not excessive pressures.

Further discussions of possible modes of ignition of dust clouds in large silos are given by Eckhoff (1987) and Alfert et al. (1989). The need for considering this problem exposes the fact that sizing of dust explosion vents is also indeed a problem of risk analysis, as outlined by Eckhoff (1986).

8. Computer modelling of turbulent dust explosions

This aspect has been reviewed by Eckhoff (1991). Considerable progress has been made during the last decade in predicting the violence of turbulent gas explosions in various industrial geometries by advanced computer simulation techniques. The pioneering work by Hjertager (1982, 1984, 1986), carried out at CMI, should be mentioned specifically.

The parameters of the explosible gas mixture used as input to the computational codes are the standard physical constants, and the laminar and turbulent burning velocities, or a global chemical induction time for ignition, as functions of gas composition, pressure, and temperature. In addition, an adequate description of the geometry of the system in which the explosion takes place must be provided to the computer. The same applies to a suitable representation of the composition distribution of the gas cloud throughout the geometry in question at the moment of ignition, and the location of the ignition source. On the basis of this information the computer code is in principle able to estimate explosion pressure and flame structure as functions of time and space.

The question in the present context is whether a similar approach is applicable to dust explosions. The two-phase nature of dust clouds complicates the modelling problem, but it seems that a comprehensive theoretical method for prediction of dust explosion violence in industrial plants may in fact be within reach. One promising attempt at developing such a model is that of Kjäldman (1992). As shown by Eckhoff (1989), the scaling of vented dust explosions in silo cells is very complex and a comprehensive computer model seems required even for this purpose.
References