Maize starch explosions in a 236 m³ experimental silo with vents in the silo wall

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Large-scale wall venting experiments were conducted in the same steel silo of 22 m height, 3.7 m diameter and 236 m³ volume used in previously published roof venting experiments. Maize starch test dust (125 kg), was blown into the silo at the top through a conventional pneumatic pipeline. The dust injection process lasted for 28 s, whereafter the air flow in the pipeline was terminated and the ignition source activated. The dust concentration in the silo was measured during dust injection. Pressure as a function of time and flame speed at different locations in the silo were recorded during each explosion experiment. In the case of an uncovered vent of 4.4 m² in the cylindrical silo wall close to the silo top, the maximum explosion pressures in the silo were generally considerably lower than with a 3.6 m² roof vent, and even somewhat lower than with a roof vent of 5.7 m². Lower turbulence, and hence combustion rate in the dust cloud in the silo, due to more restricted flow out of the vent, may be the reason for this. On the condition that adequate precautions are taken to prevent destructive effects of reaction forces, venting through the silo wall may therefore be preferable to roof venting even from the point of view of minimizing the explosion pressure.

(Keywords: explosions; silo; vents)

A comprehensive series of vented dust explosion experiments in the new 236 m³ steel silo in Norway were conducted in 1985. The vent openings were located in the silo roof. An abbreviated account was published later. The 1985 experiments showed that the maximum explosion pressure was influenced strongly by the location of the ignition point within the silo, and for this reason the main emphasis was put on quantifying this effect, which is of great practical significance.

However, it was also of considerable practical interest to investigate the feasibility of venting dust explosions in silos through vents in the cylindrical silo wall, rather than in the roof. This is because the entire roof of silos with external walls will then be available for other uses.

The main objective of the present experimental programme, conducted during the first half of 1986 and reported in detail elsewhere, was to investigate the feasibility of venting dust explosions in large silos through an opening in the cylindrical silo wall close to the silo top, as compared with venting through the silo roof. However, the strong lateral reaction forces caused by the venting of a violent dust explosion through an opening in the wall of a slender silo, close to the top, may cause the silo to overturn or break. Therefore the reaction force problem had to be given serious consideration, and adequate precautions taken.

The 236 m³ experimental silo

Figure 1 shows a sketch of the experimental site located on the island of Sotra, west of Bergen. A vertical section of the 236 m³ silo is shown in Figure 2. The silo is 22 m in height and has a diameter of 3.7 m. The main silo body is made of 8 mm thick steel plate, all-welded, and can withstand at least 5 bar internal overpressure. It is welded to a horizontal steel ring flush with the ground level, which is fixed to the solid rock underneath by 15 bolts. Sufficient strength for withstanding strong wind forces has been provided. A winding staircase is provided alongside the silo. The staircase allows easy access to any desired level. Every 1.5 m, the silo wall is furnished with a 3" threaded hole, accessible from the staircase, and permitting ignition sources and various types of diagnostic probes to be mounted in desired locations.

A strong steel grid has been constructed across the top of the silo, allowing any desired part of the roof to be blocked by bolting a number of 0.25 m² steel plates to the grid. Thus, varying vent opening areas and shapes in the roof is easy. The size and shape of the double vent used in comparative roof venting experiments in 1986, is shown in Figure 3, together with the 3.4 m² roof vent used in 1985. The free area of each grid square is 0.23 m².

Figure 4 shows a section through the silo at the level of the vent system. The total vent area of 4.4 m² is distributed on eight identical slots of height 1.23 m and width 0.45 m, separated by vertical steel beams of width = 10 cm. A fenced gangway accessible from the silo roof by a ladder was constructed alongside the entire vent arrangement, as also shown in Figures 2 and 4.

The reaction forces generated by vented dust and gas explosions have been investigated both theoretically and
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Figure 1 Sketch of experimental site with 236 m$^3$ silo equipped with vent in the silo wall

Figure 2 Vertical section of 236 m$^3$ silo

experimentally by several workers$^5^-^7$. The equation:

$$ F_{R_{\text{max}}} = 0.12AP_{\text{max}} $$

covers most published data. $F_{R_{\text{max}}}$ is the maximum reaction in MN; $A$ is the vent area in m$^2$; and $P_{\text{max}}$ is the maximum explosion pressure in bar (g). On the basis of the results of the previous roof venting experiments$^1^-^3$, it was assumed that the maximum explosion pressure would not exceed 1.5 bar(g), corresponding to a maximum lateral reaction force at the silo top of about 0.7 MN. Based on these considerations, a system of three pre-stressed wire ropes, anchoring the silo to the nearby rock, was adopted, as indicated in Figure 4. Wire ropes (20 mm thick) were found to serve the purpose. One end of each rope was fixed to specially made attachment eyes welded to the top rim of the silo, whereas the other was anchored to eye bolts molded into the nearby solid rock. Each of the two main wire ropes were pre-stressed to 0.02 MN (2 tonnes) and the third rope on the opposite side of the silo to 0.04 MN (4 tonnes).

Ignition, diagnostic and timing system

The ignition source was the same as that used in the previous experiments$^1$. It consisted of about 50 g of dried nitrocellulose powder contained in a plastic bag and fired by a pair of electrically ignited 100 J Ca-Mg fuse heads. The nitrocellulose flame was fully developed to 50–100 cm diameter approximately 0.1 s after firing the fuse heads, and it maintained its full size for approxi-
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Net vent area: 3.6 m² (1986)

Net vent area: 3.4 m² (1985)

Figure 3 The 3.6 m² roof vent arrangement used in the present experiments and the 3.4 m² roof vent used in 1985 (Ref. 1)

Figure 2 shows the locations of the various diagnostics. Three Kistler No. 7261 pressure sensors, one located 3 m above the silo bottom, one 9 m above the bottom, and one in the silo roof, were used for measuring the development with time of the explosion pressure inside the silo. Three of CMIs simplified version of the USBM light attenuation probe were used for monitoring the dust concentration development at three different points in the silo during some of the experiments. Details of the probe design and performance are provided in Ref. 1. A set of flame front detectors, consisting essentially of the receiver part of the dust concentration probes, were constructed and mounted at various altitudes along the silo wall. Finally, 25 frames per second video recordings were made of every explosion experiment.

A new, integrated data acquisition and control system was used. The system includes a 13 bit high-speed voltmeter (100 kHz), a 24-channel high-speed FET multiplexer with thermocouple compensation, and a 16-channel general purpose switch. All timing and measuring operations were automatically controlled by a computer combined with this system. More detailed information about the system is given elsewhere.

The maize starch used in the experiments

The native maize starch used was of the same type as used in 1985. Samples were taken from a number of the bags immediately before emptying the bags into the small storage hopper, from which the dust was discharged into the dust injection system. The samples were kept in sealed plastic jars and brought to the CMI lab at Fantøft for determination of moisture content and explosiveness. The moisture content in relation to wet dust was determined for samples from nine different 25 kg bags of starch, and it varied between 10.7 and 11.9 mass %, with a mean value of 11.2%. This is close to the mean value of 11.1% found in corresponding samples in 1985.

Previous particle size analyses using an Alpine air-jet
Tests of native maize starch carried out at CM1 in 1982, range 10 to 20 \mu m. This is confirmed by SEM-pictures of the starch and conforms with the fact that maize starch is essentially composed of nearly monosized and nearly spherical native grains of mean diameter about 12 \mu m.

Table 1 gives the mean values of Hartmann bomb tests of native maize starch carried out at CM1 in 1982, 1985 and 1986. Table 2 gives the mean results of 20 l sphere tests carried out at CM1 in 1985 and 1986, at FRS in 1982 and at Ciba-Geigy AG in 1985. The higher $P_{\text{max}}$ obtained in the Hartmann bomb test in 1986 as compared with the results of earlier tests can be explained when looking more closely at the test results from 1985. In the earlier tests the highest dust concentration used was 1000 g m$^{-3}$, whereas the 1986 tests revealed that the highest explosion pressures in the Hartmann bomb are in fact generated at 1500 g m$^{-3}$.

The 20 l sphere results show that Ciba-Geigy found considerably higher values for $P_{\text{max}}$ and $(dP/dt)_{\text{max}}$ than the two other laboratories. This is likely to be due to a change in moisture content of the particular sample of starch tested by Ciba-Geigy. The samples tested at CM1 had mean values of 11.1% (1985) and 11.2% (1986), and the samples tested at FRS about 10%. However, Ciba-Geigy found the moisture content of the sample tested by them to be only about 6%. Therefore, the $(dP/dt)_{\text{max}}$ value to be related to the present silo experiments is the one measured at CM1, corresponding to a $K_{\text{G}}$-value (W. German VDI 3673-system) of about 100 bar m s$^{-1}$.

### Dust injection system

As indicated in Figure 2, explosive clouds of maize starch were generated in the silo by blowing the starch into it through a conventional pneumatic conveying line of i.d. 155 mm. The starch entered the silo as a horizontal jet from the semi-tangential pipe exit close to the silo top. The air for conveying the dust was supplied by a Roots blower. With no starch in the pipeline, the upstream static pressure was very close to atmospheric and the mean linear air velocity in the pipeline was 38.3 m s$^{-1}$ (Reynolds number = 300 000). During dust injection, the static pressure would increase to typically 0.2 bar (g) with peak values approaching 0.5 bar (g), and the air flow would drop by up to 15–20%.

The maize starch was fed into the pipeline from a 1.5 m$^3$ hopper a few metres downstream of the blower by means of a rotary lock. The steady-state feeding rate was about 5 kg s$^{-1}$, which corresponds to an average dust concentration in the pipeline of about 8 kg m$^{-3}$.

When running an experiment, the blower was first started and air was blown through the system in order to dry up and clean the line. Then the air supply to the line was shut off to allow the desired quantity of maize starch to be charged into the 1.5 m$^3$ hopper at ambient pressure. The hopper was subsequently sealed, and the air from the blower was again allowed to flow freely through the pipeline. Then the rotary lock was started and run for the time required to just feed all the dust in the hopper into the pipeline, plus a few seconds to partially clear the line. Then the air flow was again shut off to allow the turbulence in the dust cloud to dissipate for a few seconds before the ignition source was activated.

### Results from vented maize starch explosions in the 236 m$^3$ silo

Control experiments using vents in the silo roof

The previous investigation was concerned with roof venting only. The overall objective of the present investigation was to study the influence of moving the vent from the silo roof to the wall near the silo top. To establish a sound basis for comparison, a few experiments with roof venting were carried out even in the present programme. The majority of the experiments were conducted with 125 kg maize starch, a dust injection period of 28 s, and a 2 s delay between shut-off of air flow and ignition. If the entire quantity of 125 kg of starch had been dispersed evenly throughout the 236 m$^3$ silo volume, the average theoretical dust concentration in the silo would have been 530 g m$^{-3}$. In reality the average dust concentration was somewhat lower, because some starch remained in the injection pipe after termination of the 28 s injection period, and some had settled on the silo floor. Furthermore, the dust concentration distribution was not uniform. However, this procedure of dust cloud generation and ignition seemed to give the most violently exploding dust clouds that could be produced by the present pneumatic injection system.

The development of the dust concentration in the silo during dust injection was followed in some of the experiments by means of three calibrated light attenuation probes. The probes were located as indicated in Figure 2 with the measurement heads approximately...
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Figure 5 Local dust concentration in 236 m$^3$ silo close to silo axis during dust injection, at 6 m and 12 m above silo bottom. Details of the probes and their calibration are given elsewhere. Figure 5 shows an example of the dust concentration as a function of time, measured at 6 m and 12 m above the silo bottom respectively. As can be seen, the concentration at the moment of ignition (30 s) was about 400 g m$^{-3}$ at 6 m and slightly lower, about 350 g m$^{-3}$ at 12 m.

The maximum explosion pressures generated in the roof venting experiments, which were all conducted at the worst-case conditions of the dust cloud generation system used, have been plotted in Figure 6 as a function of the location of the ignition source above the silo bottom. The $P_{\text{max}}$ values given are those measured by the lowest pressure transducer ($P_1$ in Figure 2). The maximum pressure measured by the intermediate transducer $P_2$ was generally only slightly lower than that measured by the $P_1$, whereas transducer $P_3$ in the silo roof generally gave lower values than the two others.

Figure 6 also gives the maximum pressures found in the previous experiments using a 3.4 m$^2$ vent in the silo roof and worst-case dust clouds. It is seen that the results from the present investigation using the 3.6 m$^2$ roof vent arrangement (Figure 3) are essentially identical with the results from the previous programme using the 3.4 m$^2$ roof vent arrangement (Figure 3). This is assumed to imply that the concentration distributions of the experimental dust clouds used in 1985 and 1986 were essentially the same. It then follows that the results from using a 5.7 m$^2$ roof vent in the previous programme are also directly comparable with these results.

Experiments using 4.4 m$^2$ vent area in the silo wall close to the silo top
The results of the 16 main experiments using 4.4 m$^2$ vent area in the silo wall close to the silo top are plotted
in Figure 7. In all the experiments the dust clouds were generated in the same way as in the experiments with roof vent, i.e. 125 kg of maize starch was injected at the silo top over a period of 28 s and the ignition source was activated 2 s after termination of dust injection. Figure 7 also shows the envelope from Figure 6 and the corresponding envelope from the previous 5.7 m$^2$ roof vent experiments. It seems clear that the 4.4 m$^2$ wall venting pressures are generally considerably lower than those from the 3.4–3.6 m$^2$ roof venting experiments, and even somewhat lower than those generated with the larger 5.7 m$^2$ roof vent. The pressure versus time histories generated by the explosion vented through the silo wall were, apart from a general reduction of the peak pressures, similar to those found with roof vents.

Figure 8 shows a typical pressure development in an experiment with ignition at 13.5 m above the silo bottom. The standing-wave oscillations of frequencies 3–6 Hz (depending on gas temperature) are very similar to those observed in roof venting experiments with ignition at 13.5 m$^{-1}$. The frequency corresponds to the first harmonic of a standing wave in a one-end-open pipe of length 22 m.

Figure 9 shows a comparison of two pressure versus time histories generated in the wall vented silo in two apparently identical experiments, with ignition at 4.5 m above the silo bottom. The upper trace exhibits a distinct spiky, oscillatory pattern after the first main pressure rise. This corresponds closely to the 17–18 Hz oscillations observed previously$^1$ with ignition at 4.5 m above the silo bottom using a roof vent. The exact nature of these oscillations has still not been resolved. However, as indicated previously$^{2,3}$, one possible explanation could be generation of some kind of Helmholtz oscillations across the vent opening during a short phase of the explosion, when the dust cloud outside the vent explodes. This will occur just after the flame front inside the silo has reached the vent opening, i.e. when the total pressure pulse reaches its peak.
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The pressure versus time history in the upper half of Figure 9 shows that the main pressure peak was reached at 1.04 s after ignition, whereas the video recordings showed that the first sign of flame reached the vent opening some time between 0.92 and 0.96 s after ignition. During the short duration of the unconfined explosion just outside the vent the over-pressure in this region may be close to the pressure inside the silo, and Helmholtz oscillations may take place. The fact that the oscillations only occur occasionally, as illustrated by the smooth, bell-shaped pressure versus time history in the lower half of Figure 9, suggests that rather unstable conditions must be fulfilled for the oscillations to appear.

The trace in the upper half of Figure 9 is from transducer $P_1$ (Figure 2), whereas the traces from all three pressure transducers are shown in the lower half. As can be seen, $P_1$ and $P_2$ gave almost identical results, whereas $P_3$, located in the silo roof, gave a slightly lower peak pressure. This pattern was observed consistently, using the 4.4 m² vent in the silo wall.

Flame front propagation in silo during vented explosions

The arrival times of the flame front at the vent opening at the silo top were determined from the video recordings of the explosions. The moment of ignition of the dust cloud inside the silo was made visible on the video by synchronizing the firing of a flash lamp mounted outside the silo, with the firing of the ignition source inside. As in the previous experiments, a close correlation was found between the moment of arrival of the flame at the vent and the moment of the main pressure peak. The pressure peak generally occurred slightly later than the flame arrival, by about 0.05–0.1 s.

An average axial flame front speed was estimated by dividing the distance from the ignition point to the vent by the time from ignition till the first appearance of flame at the vent (video). In the case of ignition at the bottom of the silo, explosions with the 3.6 m² vent in the silo roof gave about 26 m s⁻¹, whereas with the
4.4 m² wall vent they gave significantly lower values, in the range 19–21 m s⁻¹.

The vertical propagation of the flame front along the silo wall was measured by means of a number of infrared radiation detectors mounted 10 cm from the silo wall. The detectors, developed at CMI, are described elsewhere⁷. In some experiments the flame arrival was detected simultaneously at different flame probes up to several metres apart. Figure 10 gives an exaggerated illustration of a possible reason for this observation. If ignition takes place at the silo bottom and the explosion is vented at the silo top, the strong axial flow towards the vent opening will cause a marked axial stretch of the flame. Therefore, as the flame front approaches the vessel wall, it will become nearly parallel with the wall over quite long distances.

It is of interest to compare the average axial flame speeds estimated from the video recordings with those found in comparable roof venting experiments (ignition at silo bottom, worst-case dust concentration) conducted in 1985¹. With 3.4 m² vent area average flame speeds of 25–30 m s⁻¹ were measured, in complete agreement with the value of 26 m s⁻¹ for the 3.6 m² roof vent in the present investigation. Further, the previous experiments showed that a larger roof vent, of 5.7 m², gave higher average flame speeds, in the range of 30–35 m s⁻¹. This is most probably due to a larger vent allowing a higher flow rate at a given pressure drop than a smaller vent. Following this line of thought it may at the first glance seem somewhat strange that a 4.4 m² vent gave a significantly lower average flame speed, about 20 m s⁻¹, than the 25–30 m s⁻¹ found with the smaller roof vent of 3.6–3.4 m².

**Why does a vent in the silo wall give less violent explosions than a roof vent of the same size?**

Earlier this century, gas explosion experiments in long pipes have 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 explosions, to detonation⁹. It was also observed that this change of explosion violence was greatest when the pipe was closed at one end and open at the other, and ignition took place at the closed end.

The secret of the dramatic flame acceleration has also been 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 unburnt 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, whose key mechanism is the generation of flow-induced turbulence in the gas ahead of the flame.

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. For this reason venting of dust explosions in elongated enclosures of L/D > 4 is a very complex process. The turbulence generated ahead of the flame due to expansion-induced flow, has a strong enhancing influence on the combustion process. This is why the location of the ignition point with respect to the vent, is of such crucial importance for the pressure build-up during dust explosions in the 236 m³ silo. If ignition occurs in the upper part of the silo, close to the vent, there is no possibility of generating high-velocity flow and resulting high turbulence levels in the unburnt cloud further down.

It seems that this overall conception can in fact offer a qualitative explanation of why in the present experiments in the 236 m³ silo the wall vent gave considerably lower explosion pressures silo than the roof vent of similar size. Venting through the silo wall forces the dust cloud to change flow direction by about 90 degrees to pass through the vent. This necessarily increases the pressure drop across the vent, i.e. the resistance to vertical flow in the silo. Had the rate of combustion of the dust cloud been independent of the flow-induced turbulence, the reduced flow rate through the wall vent would clearly have resulted in higher maximum explosion pressures than venting through a roof vent of similar size. However, as discussed above, the measured average axial flame front speed of 20 m s⁻¹ for a 4.4 m² vent in the silo wall, is considerably lower than the speed of about 30 m s⁻¹ estimated for a roof vent of the same size. This would imply that the overall combustion rate was higher with the roof vent and probably more than compensated for the initially lower pressure drop across the vent. The net result would be a higher maximum explosion pressure with the roof vent.

As discussed elsewhere¹⁰, computer simulation of the propagation of dust explosions is the probable long-term solution for quantifying the influence of flow-induced turbulence on the combustion rate. However, developing fully comprehensive computer codes for dust explosions is a very demanding task and will take time. An intermediate solution for the time being could be to use the advanced computer codes for gas explosion simulations that have recently been developed at CMI¹¹, taking the dust cloud as being equivalent to some explosive gas mixture. Such simulations would most probably indicate whether the above suggestion of why wall venting gives lower maximum explosion pressures than roof venting, is valid. This type of simulation seems to offer a promising possibility of studying the influence of geometry on gas and dust explosions in a
variety of different configurations, such as head houses and bottom tunnels in grain storage facilities.

Conclusions

In the case of a 4.4 m² vent in the silo wall, the maximum explosion pressures generated in the 236 m³ silo were generally significantly lower than with a roof vent of similar size. Ignition just above the silo floor still gave quite high pressures of 0.7–0.8 bar(g), but a roof vent of similar size would give about 1.0 bar(g). With ignition at 7.5 m above the silo floor, the maximum pressures were 0.2–0.3 bar(g), as opposed to 0.4–0.6 bar(g) estimated for the vent in the roof. Ignition at 18 m, i.e. close to the silo top, gave very low pressures, of the order of 0.01 bar(g). The probable reason for this somewhat unexpected effect of locating the vent in the wall, is that the higher pressure drop caused by a wall vent, compared with a roof vent of similar area, restricts the vertical flow of unburnt dust cloud in the silo during the explosion. This in turn restricts the build-up of flow-induced turbulence, and limits the combustion rate of the dust cloud and the resulting rate of pressure build-up in the silo.

The strong influence of the location of the ignition point on the maximum pressure in the wall-vented 236 m³ silo explosions is in agreement with the results of previous roof-venting experiments. This re-emphasizes the importance of identifying likely ignition source locations in silos in practice.

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