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Explosion Isolation Challenges in Large-Volume Silos

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In industries that handle biomass in form of woodchips or other solid materials in larger quantities, storage silos are usually present. The main explosion safety hazards are observed during filling and emptying of the silos where potentially explosive dust clouds can be formed. In the present paper the various types of silos are presented, focusing on the phenomena observed during deflagration related to pressure rate of rise in and explosion propagation from large volumes. Protection methods are presented and compared taking into account the discussed phenomena.

1. Introduction

Statistics show that a substantial percentage of dust explosions occur in silos where combustible material such as biomass, wood chips or other organic products are stored. These bulk products carry inevitably a portion of fine particles that can form dust clouds during filling/emptying processes and are the cause of explosion. Once an ignition source such as a glowing ember or electrostatic discharge reaches a dust cloud, the deflagration's pressure will challenge the strength of the vessel, causing it to deform or even fail. Flames and pressure will also propagate through the silo's inlets and outlets and into other areas of the production process, resulting in a chain reaction of secondary explosions.

The strategy of protection against these explosions is to take measures to reduce the extend and duration of dust cloud formation, eliminate the potential ignition and install protection systems/devices that mitigate the explosion effects. Such protections systems/devices are vent panels, that break at a controlled low pressure and relief the remaining pressure build-up or suppression systems that disperse inert powder in the silo volume as soon as a initiating explosion is detected. Moreover, explosion isolation is also required to prevent, or minimise, the possibility that an explosion starting in one piece of equipment propagates along the interconnection network to adjoining items of the plant. Explosion isolation is typically realized by mechanical valves, which can be installed in ductwork, or chemical barriers with containers of extinguishment powder installed on conveyors. All these protection systems need to be designed in order to effectively stop the potential explosion but explosions in large volumes have different features than in small volumes that can be reproduced in a laboratory.

Considering explosion duration and flame speed, the main objective of the present paper is to provide an overview of the factors that affect the explosion protection methods and how these are differing in large volumes such as silos based on literature.

2. Types of Silos

Silos are categorized generally as horizontal (bunker) or vertical (tower). Horizontal silos can be as an above-ground bunker, have the form of a trench or be a standalone silage bag. These types of silos are generally used for their large storage capacity where 400 tons or more of silage is required (Clark et al., 1998). Hazards of confined space operations are present in such volumes, where gases can be produced; as a result spontaneous ignition may occur. Some examples of such structures are shown in Figure 1.

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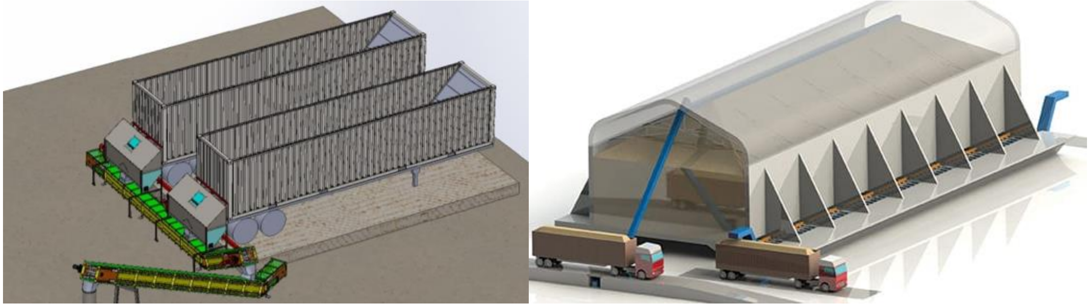

Figure 1. Examples of horizontal silos (BE&E, 2016).

Vertical or tower silos are vertical cylindrical volumes, typically 10 to 90ft (3 to 27m) in diameter and 30 to 275ft (10 to 90m) in height. The two most important types of vertical silos are conventional and oxygen-limiting (or controlled atmosphere). Conventional silos are the most common type of silo. They are usually built on a concrete base constructed of concrete staves with steel bands bided together. An unloading chute runs the vertical length of the exterior of the silo and are covered on top by a loosely constructed dome. At the dome generally there is a fill tube and a loading door on the side. Conveyor belts many times are located directly below the unloading chute to transfer silage in nearby feedlots. The oxygen-limiting silo is designed as solid construction to be nearly air-tight, constructed of steel shells with inner layer of glass and outer enamel or ceramic coating. The primary identifying feature of oxygen-limiting silos is the absence of the unloading chute on the exterior. A fill door is usually located in the center of the top of the silo roof, a roof hatch, a center fill pipe attached to a fill pipe, or a single unloading door at the bottom of the silo. Filling is done through the top and unloading from the bottom. Schematics of these types of silos are presented in Figure 2.

All the aforementioned types of silo have different pros and cons on the storage of biomass and are widely used for such applications.

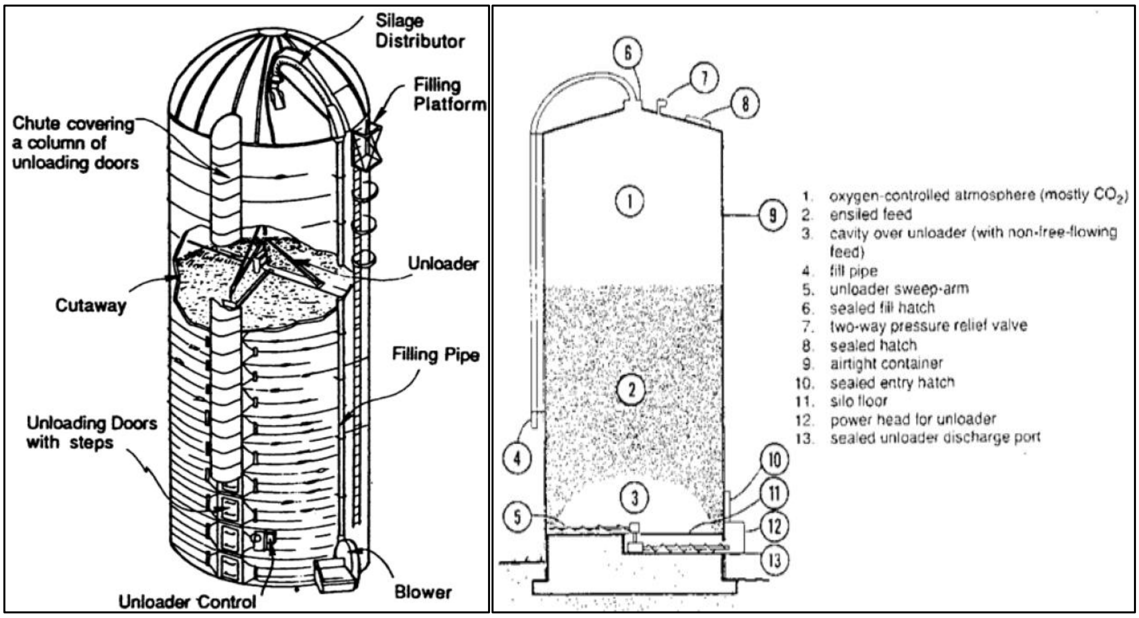

Figure 2. The schematic of a conventional silo (left) and a limiting oxygen silo (right).(Clark et al., 1998)

3. Explosion Risks in Silos and Large Volumes

Biomass can be at the form of wood chips, wood pellets, dried sewage sludge etc. In addition there is extensive use of wood chip and “wood flour” in the chipboard, Fibre board and MDF manufacturing industries. Biomass is an inherently dangerous category of substances, especially in bulk (Ennis, 2016). More particularly, dust explosions pose a hazard whenever a certain amount of combustible powder is present; the powder can be dispersed in air to form an explosive dust-air cloud within a confined volume, and there is an ignition source present. The deflagration of such cloud within the silo volume results in blast effects including, flame ejection, pressure effects and projectiles with possible explosion propagation into upstream interconnected equipment.

These dust clouds are present during filling/emptying processes inside and outside the silos. Depending on how often the silo is filled, dust clouds could be intermittent or continuously present.
Ignition can be occurred by self-heating of the silage, mechanical friction, malfunctioning of electrical apparatus or even lighting as silos are very tall structures. Self-heating occurs when the moisture levels of the silage are not proper. The material reacts with the oxygen until the process becomes anaerobic and the fermentation comes to a stable state. This anaerobic process within a few weeks (up to few years) causes increase of the temperature of the silage so that a self-ignition can occur. Mechanical friction from conveyors, belts or other mechanical apparatus can provide enough ignition energy to initiate a deflagration. Electrical circuits or motors can create the same ignition conditions through arcing or overheating during function. Furthermore, in silos filled at a high rate using methods such as pneumatic conveying, dust can accumulate significant static charge.
Dust deflagrations have certain characteristic values that define the intensity of the explosion. The most common are: $Pmax$ defined as the maximum pressure that can be reached in a confined volume during explosion and the deflagration index defined by

$$Kst = \frac{dP}{dt} \times V^{\frac{1}{3}} \equiv constant \quad (1)$$

Where dP/dt is the rate of rise of pressure and V is the vessel volume. This deflagration index is constant for the same dust concentration and particle size dispersed in different volumes of similar geometry. This value provides information on the explosion violence and is numerically equal to the maximum rate of pressure rise in the 1 m^3 standard ISO 6184 test (Eckhoff, 2003). Except from the combustion properties of the dust material, the explosion violence is also dependant on turbulence. By applying Eq.1 to very large volumes it can be concluded that the rate of pressure rise will reduce as depicted qualitatively in Figure 3. The rate of which pressure increases is directly linked with flame speed and combustion volume; Since flame speed remains mainly unaffected by volume, the explosion duration can take up to some seconds to complete. Other common dust characteristic parameters are the MIE (minimum ignition energy), MIT (minimum ignition temperature), but not discussed in the present text, because they mainly relate to the likelihood that ignition will take place.
Eckhoff (2003) emphasizes that the important features of an explosion in a large grain silos are unlikely to be reproduced in a small scale laboratory silo models and recommends that the dust flame propagation should be studied in large-scale apparatus. Tests conducted in large silo volumes indicate that the duration of the flame lasts more than 3sec and, under certain conditions, its motion is vibratory. More specifically, when vents open, the flame exits in puffs instead of in a continuous stream (Eckhoff (2003)) as seen in Figure 4. This kind of oscillatory pressure development occurred only when the ignition point was on the upper half of the silo and the peak pressure of these oscillations appears 2sec after ignition.

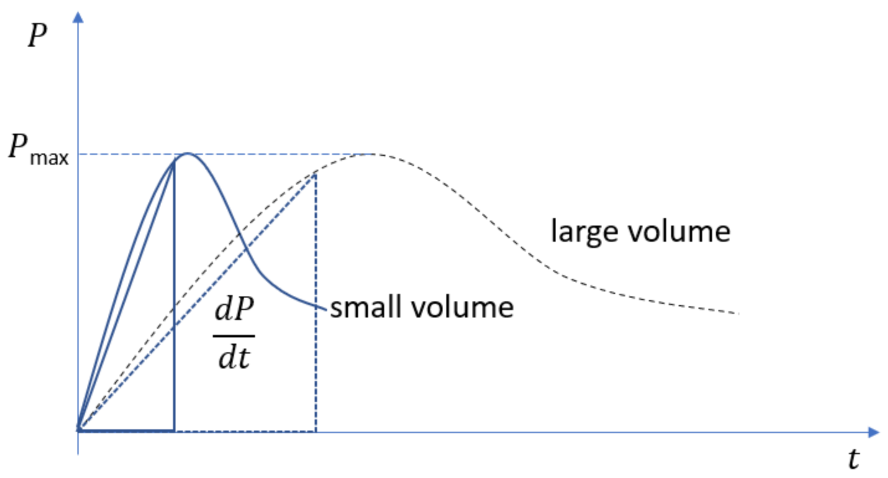

Figure 3. Diagram of pressure vs time showing the difference in rate of pressure and explosion duration for two different volumes; the larger volume is represented by the dashed line.

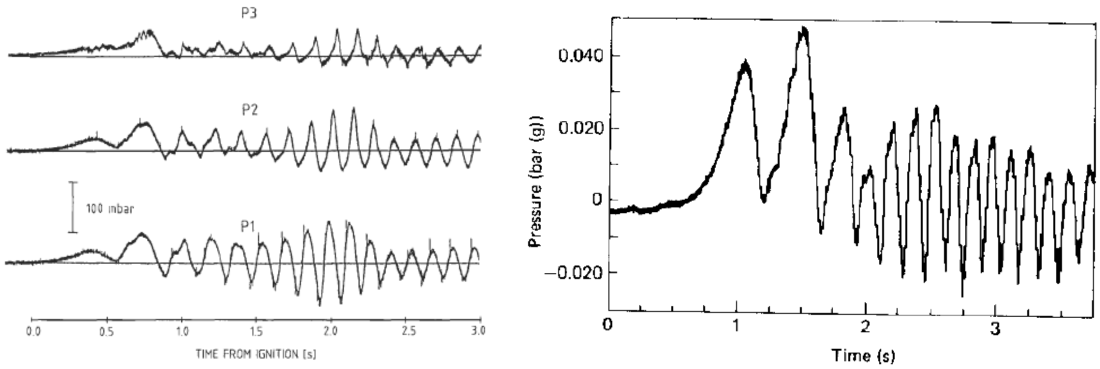

Figure 4. Left: Oscillatory pressure development resulted in the ignition of the upper half of a silo of 236m³. The fuel is cornstarch 600g/m³ and vented on the roof with 5,7m² vents. Right: Pressure vs time measured at 3m above the bottom of the silo. Figure as seen in Eckhoff (2003), Eckhoff (1988) and Eckhoff (1984).

4. Deflagration duration in large silos

Besides from Eckhoff (2003), experimental evidence with dust deflagrations in large volumes such as in Silos is scarce. Most experimental evidence exists in small to medium sized volumes. However, by observing how the deflagration behavior changes from small to medium sized volumes, it is possible to give reliable approximations of the deflagration behavior in very large volumes.
Following observations are made from experiments:

- Flame speed is more or less independent of volume.
- Flame speed is more or less linear proportional to the dusts Kst value and inverse proportional to the dust's $Pmax$ value.

From the above observations, one can conclude that in a spherical volume entirely filled with a homogenously dispersed dust cloud and ignited in the sphere's center, the deflagration duration relates to the sphere's volume as follows:

$$duration \sim P_{max} \cdot \frac{V^{\frac{1}{3}}}{K_{st}} \qquad (2)$$

Although the observed flame speed depends on the dusts Kst value, a real explosion in a Silo is often less intense and slower propagating than measured in a test lab under 'ideal' combustion conditions. To estimate the longest possible duration of a deflagration in a very large volume, one should therefore assume a mild, slowly propagating explosion, for instance with low dust concentration and low turbulence levels in the dispersed dust cloud. To represent the worst case with respect to deflagration duration, it is proposed to take a low Kst value of 50 bar.m/s, independent of the Kst value of the dust measured in the lab.
In order to stay on the conservative side, $Pmax$ is set to 10 barg in the equation above. This $Pmax$ value covers a large range of biomass dusts.
Based on the above and more detailed modelling and experimental comparison, following formula is proposed to estimate a conservative value for the deflagration duration in very large volumes:

$$duration \leq 3 \times 10barg \times V^{\frac{1}{3}} \Big/ 50bar.\frac{m}{s} \qquad (3)$$

Results of the proposed formula comparted with literature findings are summarized in **Errore. L'origine riferimento non è stata trovata.**. It should be noted that Eq. 2 is based on spherical vessels with central ignition. Overall it can be seen from Table 1 that the estimations provided by the formula are acceptable comparing either with simulations or real experiments. Elongated vessels with ignition at the bottom, and explosion venting panels at the roof, may not represented well by this formula. However, it is also observed that is such constellations flame speeds starts to increase during deflagration propagation from silo bottom to upwards, especially when the venting panels have burst (Eckhoff, 2003).

Table 1. Comparison of the prediction with literature data.

Reference	Volume (m^3)	Kst(bar.m/s)	Pmax(bar)	Predicted Duration(s)	Actual Duration(s)
Abuswer, 2013	400	104	6,7	1,4	1
Abuswer, 2013	400	15	5,8	8,5	4,5
Abuswer, 2013	200	15	5,8	6,7	4
Abuswer, 2013	500	132	7,3	1,3	1
Abuswer, 2016	304500	188	9,6	10,3	10
Eckhoff, 1984	500	325	7	0,5	0,3*
Eckhoff, 1988	236	248,5	7,3	0,5	0,4**

*this is the duration of the pressure curve where the silo ruptured.
**ignition at the bottom of the silo.

5. Protection methods

Controlling the explosion hazards in large volumes requires good process safety design and careful operational management. One of the most common methods to provide explosion protection is to vent the silo volume by applying vent panels. The two main standards developed for such application are NFPA 68 and EN14491 where they provide vent sizing equations. The equations in are limited to a maximum volume of 10,000m³ and extrapolation beyond this value is potentially hazardous. The size of biomass silos can considerably exceed the maximum volume of the venting standards, with several modern installations being an order of magnitude larger. CFD modelling can be used to estimate the required explosion vent size. It should be noted that the assumptions made during the CFD model can have a significant impact on the accuracy of the calculations. The only CFD model validation is based on experiments carried out in 200-300m³ scale units similar to the ones discussed in the present text.

Figure 5. Vent panels installed on the top of a silo.

Suppression systems that disperse inert powder in the silo volume as soon as a spark is detected can be also used to protect the facility against explosion. An explosion suppression system composed of explosion detector(s), explosion suppressor(s) and a central control unit. Hardware is normally bolted onto flanges that are welded into the plant component. Suppressors must be located to deploy suppressant into the explosible volume and the fixings must be designed to withstand the reaction force of the suppressor discharge, and to support the weight of the suppressors. The detector senses the explosion and triggers automatic high rate discharge explosion suppressors. The suppressant charge is discharged into the fireball to extinguish all combustion resulting into lowering the pressure. The suppressant discharged into the component renders the conditions within the plant inert for a time, and for large volumes it is important to ensure that there is no re-ignition. Its effectiveness depends on the reliability of the installed components. The range of volumes that can be suppressed effectively is starting from 0,25m^3 up to 1000m^3.
Thought should also be given to the risk of explosions in other interconnected vessels propagating into the silo. Isolation devices can block both exit and entry of explosions from and to vessels. It’s common for explosion protection providers to recommend isolating a silo’s filling chute with a chemical isolation system, consisting of multiple bottles depending on the volumes and hazard. However, protecting large-volume silos with chemical isolation are challenged by the long-duration of deflagration as discussed in the previous section. If a chemical

isolation bottle empties its contents within one second and the duration of the explosion exceeds the life of the chemical barrier, flames can still propagate into interconnected equipment. Moreover, due to the low rate of pressure rise pressure detectors do not activate timely, as a result optical detection is required.
In the latest years mechanical isolation systems have been developed installed horizontally across the filling duct of the silos, with sizes up to 1250mm x 1400mm. This kind of active system comprises a mechanical gate valve, detectors and a controller. The detection system is usually relying on optical triggering combined with pressure detectors as it is more safe approach especially for large volumes. Upon detection of an explosion, compressed nitrogen activates the piston, which closes the gate valve into a locked position within milliseconds before the pressure and flames reaches the filling chute. Chemical isolation may be used in tandem with a gate valve to protect against low minimum energy ignition (MIE) dusts, whose explosions are often more difficult to isolate. These chemical isolation units are installed between the combustible material and gate valve to ensure no sparks or flames sneak through the small remaining gaps of a closed gate valve. Tandem chemical isolation can also be required to provide explosion isolation while the valve is closing, but not closed yet (BI, 2021).

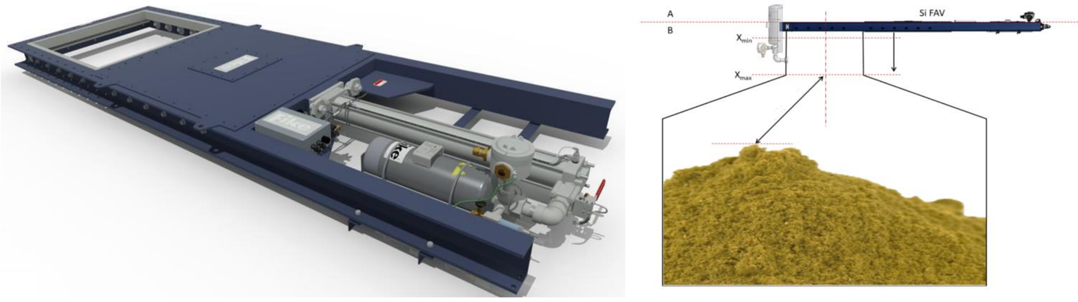

Figure 6. A typical mechanical gate valve installed at the filling chute of the silo combined with chemical isolation. In that case it is Fike's Si-FAV.

6. Conclusions

Biomass is an inherently dangerous material possessing significant fire and explosion hazards. Its use brings several challenges, especially where the scale of installations significantly exceeds the scope of any previous installation in terms of size. The traditional protection methods such as venting, suppression or chemical isolation provide sufficient support but there are certain drawbacks related to costs, footprint or performance especially due to the slow evolution of the explosion. Using a mechanical isolation valve at the chute of the silo is bypassing the issue of long duration flames or possible re-ignitions.

References

Abuswer, M., Amyotte, P., Khan, F., 2013, A quantitative risk management framework for dust and hybrid mixture explosions. Journal of Loss Prevention in the Process Industries, 26(2), 283-289.

Abuswer, M., Amyotte, P., Khan, F., Imtiaz, S., 2016, Retrospective risk analysis and controls for Semabla grain storage hybrid mixture explosion. Process Safety and Environmental Protection, 100, 49-64.

BE& E, 2016, Biomass Engineering & Equipment, Moving Floor Trailers and Bins From Biomass Engineering & Equipment, <https://www.biomassengineeringequipment.com/live-floor-trailers-bins-biomass-engineering-equipment/> accessed 10.12.2021

BI, 2021, The Challenges of Isolating Explosions in Large-Volume Silos, Bulk Inside, Explosion protection and process safety, < https://bulkinside.com/bulk-solids-handling/explosion-protection-process-safety/challenges-isolating-explosions-large-volume-silos/ > accessed 10.12.2021

Clark, A., Kimball, J. and Stambaugh, H., 1998. The Hazards Associated with Agricultural Silo Fires. Federal Emergency Management Agency, United States Fire Administration.

Eckhoff R. K., Fuhre K., 1984, Dust explosion experiments in a vented 500 m3 silo cell, Journal of occupational accidents 6, no. 4, 229-240.

Eckhoff, R.K., Alfert, F., Fuhre, K. and Pedersen, G.H., 1988, Maize starch explosions in a 236 m3 experimental silo with vents in the silo wall. Journal of loss prevention in the process industries, 1(1),16-24.

Eckhoff R. K. (Ed.), 2003, Dust explosions in the process industries: identification, assessment and control of dust hazards. Elsevier.

Ennis T. Fire and Explosion Hazards in the Biomass Industries, Hazards 26, SYMPOSIUM SERIES NO 161, Edinburgh, UK, 2016, IChemE.