Dust Explosion Venting in Silos: a Comparison of Standards

NFPA 68 and EN 14491

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Final version of this work published in:


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Abstract

Venting devices are commonly used to try to reduce the damage caused by any dust explosion that may occur in silo systems. In North America and Europe the sizing of these vent areas is governed by standards NFPA 68 and EN 14491 respectively, both of which have recently come into force. The aim of the present work was to compare these standards in terms of the cost of protecting against dust explosions. Vent areas calculated according to NFPA 68 were smaller than those calculated in line with EN 14491, except when the silos had a length/diameter ratio of 1, when the opposite was true. The difference increases for high length/diameter ratios, especially when the reduced explosion pressure is low. The optimum design for attaining minimum protection costs according to the two standards was slightly different. As a practical example, the cost of protecting a real silo using venting panels was calculated using both standards.

Keywords: dust explosion, silo, venting, standard, cost
1. Introduction

The handling of materials stored in silos commonly leads to the formation of dust clouds that pose an explosion hazard. The materials that can cause dust explosions include agricultural and food products (grain, malt, flour, maize starch, sugar, etc.), synthetic organic materials (plastics, pigments, pesticides, etc.), metals (aluminium, magnesium, etc.), and coal (Eckhoff, 2003).

Dust explosions occur when fine particles dispersed in the air as a cloud react with oxygen in the presence of an ignition source, generating an exothermic chain reaction. When this occurs in a constant volume there is a rapid and significant increase in pressure (Eckhoff, 2003).

Prevention measures must be the first line of defence against such explosions, but in many situations attempts to eliminate ignition sources are simply not enough. Measures for mitigating the damage caused and the dangers posed to workers by eventual explosions are necessary. To help guarantee the safety of silo installations, companies in Europe are required to comply with the ATEX Directives regarding explosive atmospheres (ATEX 1999/92/EC, ATEX 94/9/EC) by installing protection mechanisms.

Venting devices are the most common protective measures used in silos; indeed, they are usually the only option. In a closed vessel with no protective system, explosion pressures can reach 7-10 bar (700-1000 kPa), placing a silo at risk of damage or even destruction. Flying fragments produced by the explosion could also injure personnel. Pressure release through the timely opening of a vent can help prevent unacceptably high pressures being reached; the sizes of such vent areas are determined following the recommendations in the corresponding standards.
Explosion venting for silos requires installing vents in the upper sidewall (always above the maximum height of the material contained in the silo), in the roof, or indeed having the entire top of the enclosure act as a vent.

European Standard EN 14491 (2006) for the venting of dust explosions came into force in 2006 and describes the basic design requirements for dust explosion venting systems. This standard is one of a series including standards EN 14797 (2006) and EN 14460 (2006) on vent manufacture and explosion resistant structures. Together, these three standards completely cover dust explosion venting regulations in Europe. The main source of EN 14491 was the German guideline VDI 3673 (2002).

The 2007 edition of the American National Fire Protection Association Standard 68 (NFPA 68) for explosion protection by deflagration venting is a complete revision of the Association’s previous publication; indeed, it represents an upgrade from guidelines to a standard. It now provides mandatory requirements for the design, location, installation, maintenance and use of devices and systems in the USA that vent combustion gases and reduce overpressures. The review of experimental data led to revisions of the basic equation for the calculation of venting areas, along with changes to those for determining panel inertia, the volume occupied by dust clouds, and initially elevated pressures, and the corrections to be used when vents are already in place (NFPA 68, 2007).

Other standards and guidelines for explosion venting also exist, e.g., the German technical report for silos DIN-Fachbericht 140 (2005). A comprehensive list of methods for dust explosion vent design can be found in Abbasi and Abbasi (2007) and Eckhoff (1990, 2003).
Vent areas in silos must be large enough to prevent explosion pressures reaching damaging levels, but not so large that the use of vents becomes impracticable. Vent area sizing is therefore a critical issue. However, flame propagation inside and outside vented enclosures is not well understood (Eckhoff, 1990; Eckhoff, 2005), and further work is needed to explain the unexpected results obtained in experimental work (Höchts & Leuckel, 1998).

The aim of this work, which is part of a research project on the computer simulation of dust explosions in silos (Aguado, Tascón & Ruiz, 2006), was to compare standards NFPA 68 (2007) and EN 14491 (2006) in terms of the cost involved in protecting against explosions.

2. Methodology

The European standard EN 14491 (2006) and the 2007 edition of NFPA 68 were compared. In addition, the first of these was also compared to the German guideline VDI 3673 (2002), and the second to the 2002 edition of NFPA 68.

Vent areas were calculated according to both standards. For EN 14491 (2006), the general equation for isolated enclosures and reduced explosion pressures ($P_{\text{red}}$) of <1.5 bar was used. For NFPA 68 (2007), the general equation for venting of deflagrations of dusts and hybrid mixtures, which determines the minimum necessary vent area in low or medium turbulence conditions, was used and the result was adjusted by applying the L/D correction if the L/D ratio was greater than 2. Table 1 shows the limitations of these empirical equations.
**Table 1.** Limits for equations given by the standards.

<table>
<thead>
<tr>
<th>Variable</th>
<th>EN 14491</th>
<th>NFPA 68</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel volume (V)</td>
<td>$0.1 \leq V \leq 10000 \text{ m}^3$</td>
<td>$0.1 \leq V \leq 10000 \text{ m}^3$</td>
</tr>
<tr>
<td>Static activation pressure of venting device ($P_{stat}$)</td>
<td>$0.1 \leq P_{stat} \leq 1 \text{ bar}$ for $P_{stat} &lt; 0.1 \text{ bar}$, use $P_{stat} = 0.1 \text{ bar}$</td>
<td>$P_{stat} \leq 0.75 \text{ bar}$</td>
</tr>
<tr>
<td>Reduced explosion pressure ($P_{red}$)</td>
<td>$P_{stat} \leq P_{red} \leq 2 \text{ bar}$</td>
<td></td>
</tr>
<tr>
<td>recommended value $P_{red} \geq 0.12 \text{ bar}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum explosion pressure ($P_{max}$)</td>
<td>$5 \leq P_{max} \leq 10 \text{ bar}$ for a $K_{st}$ value of 10 bar.m.s$^{-1}$ $\leq K_{st} \leq 300 \text{ bar.m.s}^{-1}$</td>
<td>$5 \leq P_{max} \leq 12 \text{ bar}$ for a $K_{st}$ value of 10 bar.m.s$^{-1}$ $\leq K_{st} \leq 800 \text{ bar.m.s}^{-1}$</td>
</tr>
<tr>
<td>Length-to-diameter ratio (L/D)</td>
<td>$1 \leq L/D \leq 20$</td>
<td>$L/D \leq 8$ (for top-fed containers)</td>
</tr>
<tr>
<td>Turbulence</td>
<td>average air axial velocity and tangential velocity both $&lt; 20 \text{ m/s}$</td>
<td></td>
</tr>
<tr>
<td>Atmospheric conditions</td>
<td>atmospheric pressure between 80 and 110 kPa</td>
<td>initial pressure of 1 bar absolute $\pm 0.2$ bar</td>
</tr>
<tr>
<td>temperature between -20 $^{\circ}$C and 60 $^{\circ}$C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>relative humidity between 5% and 85%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume fraction oxygen content $20.9 \pm 0.2%$ volume fraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Further conditions</td>
<td>no vent ducts (nearly inertia free device)</td>
<td>no vent ducts (panel inertia $\leq 40 \text{ kg/m}^2$ (and $\leq M_f$ or threshold mass calculated in equation 8.2.7.2 NFPA 68))</td>
</tr>
</tbody>
</table>

The influence of the variables contemplated in the calculation of venting areas was studied to determine whether designers can reduce the vent area required and therefore reduce protection costs (Table 2). Cylindrical silos of 1000 m$^3$ with an L/D ratio ranging from 1 to 3, flat-bottomed and with vents in the roof, were selected for all comparisons.
Table 2. Ranges of values for the different variables taken into account in this work.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (V)</td>
<td>1000 m$^3$</td>
</tr>
<tr>
<td>Length-to-diameter ratio (L/D)</td>
<td>1, 1.5, 2, 2.5 and 3</td>
</tr>
<tr>
<td>Reduced pressure (P$_{\text{red}}$)</td>
<td>0.12, 0.30, 0.50 and 1 bar</td>
</tr>
<tr>
<td>Static activation pressure of the venting device (P$_{\text{stat}}$)</td>
<td>0.10 and 0.05 bar</td>
</tr>
</tbody>
</table>

The vent area for four reduced explosion pressures (P$_{\text{red}}$) was determined using both standards. The lowest P$_{\text{red}}$ selected in both cases was 0.12 bar, which is the minimum value recommended by EN 14491 (2006), although the lower limit in this standard is P$_{\text{red}}$ ≥ P$_{\text{stat}}$ ≥ 0.10 bar (see Table 1).

The storage of several bulk materials were taken into account, the explosion characteristics of which were determined by García et al. (2005) and Skjold et al. (2005) (see Table 3).

Table 3. Explosion characteristics of different agricultural materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>$P_{\text{max}}$ (bar)</th>
<th>$K_{\text{st}}$ (bar.m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>7.1</td>
<td>50</td>
</tr>
<tr>
<td>Maize</td>
<td>7.5</td>
<td>81</td>
</tr>
<tr>
<td>Wheat flour</td>
<td>8.1</td>
<td>144</td>
</tr>
<tr>
<td>Maize starch</td>
<td>8.6</td>
<td>149</td>
</tr>
</tbody>
</table>

The variable ‘vent area/silo volume’ (venting index) (see Eq. 1) was used in the determination of the total protection costs per cubic metre of storage volume. This allows explosion protection costs to be incorporated into decision-making regarding silo design. In this work, to facilitate the drawing of graphs, the venting index was multiplied
by 100 \((A_{v=100})\), i.e. \(A_{v=100}\) represents the vent area required for 100 m³ of storage volume.

\[
A_{v=100} = (A / V) \cdot 100
\]

(Equation 1)

where

\(A_{v=100}\) = venting index for a volume of 100 m³ (m²)

A = total vent area of the silo (m²)

V = total volume of the silo (m³)

3. Results and discussion

The formulae used to calculate the required vent area in isolated enclosures offered by standard EN 14491 (2006) and the German guideline VDI 3673 (2002) are exactly the same. However, these standards recommended their corresponding equations be used over a slightly different range of conditions, e.g., VDI 3673 contemplates operating overpressures up to 0.2 bar compared to 0.1 bar in EN 14491, and specifies no limitations regarding relative humidity or temperature. Further, the alternative formulae provided in Annex A of VDI 3673 do not appear in the latest European standard. These alternative formulae can be used to determine the vent area required for the pneumatic conveying of products with axial or tangential release into silos, as well as in free-fall filling. The vent areas calculated in line with these alternative equations are significantly smaller than those returned by the general equation. Research has shown the concentrations of dust and turbulence in real large silos to be much lower than those generated by the method outlined in VDI 2263 (1992), which was used to obtain the general equation in EN 14491 (Hauert, Vogl & Radant, 1994). The main limitation of the VDI 3673 alternative method is the strict boundary condition
for the feed rate when the material is introduced into the vessel by free fall from a rotary valve or screw feeder.

Figures 1 and 2 show the vent areas required by the two studied standards for the storage of maize in silos of the same size. The results obtained for the other materials (Figure 3) are analogous (quantitatively different but qualitatively similar), and follow the same trends. The vent area depends on the characteristics of the dust ($K_{st}$, $P_{\text{max}}$): the higher the deflagration index $K_{st}$ or the maximum pressure $P_{\text{max}}$, the greater the vent area required. The influence of the product stored is therefore important (Fig. 3); for example, the vent area when storing maize starch is three times that required for storing barley.

Given the required vent areas returned by the different standards, venting could be technically difficult in some silos and represent an economic burden. Commercial vent panels would be costly for small and medium-sized food industries needing large storage volumes. It should be remembered that the vent area should not exceed the silo diameter (as the NFPA 68 standard explains); this is also applicable to silos protected by vent devices installed on the upper sidewall. In practice the available area for installing vent devices may be smaller due to structural or technical limitations.

Figure 1 shows the equation in NFPA 68 defines four constant values up to $L/D=2$, one for each $P_{\text{red}}$ value. Thus, the vent area is independent of the $L/D$ ratio up to $L/D=2$. The correction for $L/D$, which increases the vent area, is only applied for $L/D>2$. A lower $P_{\text{red}}$ results in a larger vent area.
Figure 1. Vent area according to NFPA 68. Maize. V=1000 m$^3$, $P_{stat}=0.1$ bar.

Figure 2 shows vent areas calculated in accordance with EN 14491. In this case the equation defines four smooth curves for different $P_{red}$. The correction for L/D starts at L/D=1; thus, the vent area always increases with the L/D ratio.

Figure 2. Vent area according to EN 14491. Maize. V=1000 m$^3$. $P_{stat}=0.1$ bar.
Figure 3. Vent area required by EN 14491 for several agricultural and food products. V=1000 m³. \(P_{\text{red}} = 0.3\) bar. \(P_{\text{stat}} = 0.1\) bar.

The vent areas calculated according to EN 14491 were larger than those calculated in line with NFPA 68 for all cases analysed except for an L/D ratio of 1. The difference increases for high L/D ratios, especially when the \(P_{\text{red}}\) is low. Figures 4 and 5 compare the standards for low maximum reduced overpressures of 0.12 and 0.3 bar; these are the most problematic values as they require large vent areas.
Figure 4. Comparison of vent areas required by NFPA 68 and EN 14491 for maize.

V=1000 m³. $P_{\text{red}}=0.3$ bar. $P_{\text{stat}}=0.1$ and 0.05 bar.

Figure 5. Comparison of vent areas required by NFPA 68 and EN 14491 for maize.

V=1000 m³. $P_{\text{red}}=0.12$ bar. $P_{\text{stat}}=0.1$ and 0.05 bar.

In Figures 4 and 5 there is only one curve for EN 14491, as this standard states that the equations for calculating vent areas are valid for static activation overpressures of $0.1 \text{ bar} \leq P_{\text{stat}} \leq 1 \text{ bar}$. When $P_{\text{stat}}$ is <0.1 bar, the equations should be used with that
minimum value. Therefore, the curves for $P_{\text{stat}} = 0.05$ bar and $P_{\text{stat}} = 0.1$ bar are the same. Standard NFPA 68 states no lower limit for $P_{\text{stat}}$, but the reduction in the vent area when vent panels of $P_{\text{stat}} = 0.05$ bar are used is insignificant.

Figure 6 compares the 2002 and 2007 versions of NFPA 68. There is very little difference in vent area up to $L/D=2$, the 2007 version returning just slightly higher values. Both documents use the $L/D$ correction when $L/D>2$. Up to this value the vent area is calculated with the formula for cube-like enclosures, and this has essentially remained the same. For $L/D$ ratios of $>2$, the difference in the results these versions return increases, especially for small $P_{\text{stat}}$ values, with the 2007 version returning smaller values. It is clear that the vent areas required by this standard are smaller than before for slender, low-strength enclosures.

![Figure 6. Comparison of NFPA 68 (2007) and NFPA 68 (2002). Maize starch. Silo $V=1000$ m$^3$. Several $P_{\text{req}}/P_{\text{stat}}$ combinations.](image)
Figures 7, 8, 9 and 10 show the venting indices for the four materials studied. They illustrate the cost of venting protection in silos and compare the North-American and European standards at different $P_{red}$ values.

![Figure 7](image)

**Figure 7.** Venting index according to NFPA 68 and EN 14491 for different L/D ratios. Barley. $V=1000$ m$^3$. Several $P_{red}/P_{stat}$ combinations.
Figure 8. Venting index according to NFPA 68 and EN 14491 for different L/D ratios. Maize. V=1000 m$^3$. Several $P_{red}/P_{stat}$ combinations.

Figure 9. Venting index according to NFPA 68 and EN 14491 for different L/D ratios. Wheat flour. V=1000 m$^3$. Several $P_{red}/P_{stat}$ combinations.
In the studied scenarios, the protection costs associated with NFPA 68 were smaller than those associated with EN14491, except for an L/D ratio of 1. The difference becomes especially noticeable at low $P_{\text{red}}$ (0.12 and 0.3 bar); for a $P_{\text{red}}$ of 1 bar the results returned by these standards are not significantly different.

When NFPA 68 is used, the minimum costs occur when $1 \leq \frac{L}{D} \leq 2$. They remain constant up to $L/D=2$, irrespective of the silo design, because the vent area does not vary for the fixed volume investigated ($V=1000 \text{ m}^3$). EN 14491 had the lowest cost at $L/D=1$, increasing with this ratio. The L/D correction therefore influences the cost and explains the different behaviour of the compared standards.

For both standards the cost of protection increases as $P_{\text{red}}$ decreases. The influence of $P_{\text{red}}$ is very significant, especially when using EN 14491 and the L/D ratio is high.
The equations in EN 14491 are proposed for calculating vent areas for an enclosure completely filled by a turbulent dust cloud of optimum dust concentration. However, in some practical situations, such as in silos (especially when a free fall or mechanical feeding mechanism is used) the test procedures employed in European standards tend to overstate explosion intensities. European standard EN 14491 specifies that, for non-homogeneous dust clouds of low dust concentration under conditions of low to moderate turbulence, a reduced vent area can be used. However, no value or alternative formula is suggested for calculating this area. Rather, it requires it be determined by explosion venting trials. In this respect, the alternative formulae presented in Annex A of VDI 3673 (2002), which were not included in the new European standard, may be a useful tool. These alternative formulae return notably smaller vent areas (Fig. 11).

In contrast, the NFPA 68 (2007) equation applies to an average axial and tangential air velocity of <20 m/s. For high-velocity situations (which develop strong turbulence), high-turbulence corrections need to be applied for calculating the vent area.
Figure 11. Comparison of general formulae in EN 14491 (continuous lines) to alternative formulae in Annex A VDI 3673 (broken lines). \( V = 1000 \text{ m}^3 \). Maize starch.

\( P_{\text{stat}} = 0.1 \text{ bar} \). Several \( P_{\text{red}} \).

Figures 12 and 13 show the influence of the vessel volume on the venting index. For a fixed L/D ratio, the venting index becomes smaller as the volume of the silo becomes larger. However, the vent area required by the studied standards always increases as the vessel volume increases, since there are more gases to release. This highlights the difference between the vent area and the venting index.
Figure 12. Influence of volume on the venting index according to NFPA 68 for a fixed length to diameter ratio (L/D=1.5). Maize. P_{stat}=0.1 bar. Several P_{red}.

Figure 13. Influence of volume on the venting index according to EN 14491 for a fixed length to diameter ratio (L/D=1.5). Maize. P_{stat}=0.1 bar. Several P_{red}. 
3.1. **Real example**

The following is an example of a real situation - a steel silo - to illustrate the cost of explosion venting protection determined according to EN 14491 (2006) and NFPA 68 (2007). Price information about the steel structure was supplied by several Spanish companies marketing such silos. The vessel considered in this example is a steel cylindrical silo of 1000 m$^3$ capacity, made of corrugated plates.

It was decided that the vent panels be installed in the roof since the silo studied was part of a silo battery. The roof is almost conical in shape, made of trapezoid steel plates. Stainless steel vent panels of 1492x450 mm (outer dimensions) were selected, with a vent area of 0.5217 m$^2$ per unit. These panels fit properly in the plates of the silo roof. The price was around 230 € per unit, including the framework, and it was supplied by several companies marketing such vent panels in Spain (this price does not include packing, delivery or assembly costs). It is important to remark that the price of the vent panels depends on the total number of panels ordered. In this example it was supposed that the silo was part of a silo battery in a factory and the total number of commercial vent panels ordered was important. Increments in price per square metre can reach 50% depending on the number of units and size of the vent panels ordered.

The characteristics of the silo and the dust were as follows:

Silo capacity (V): 1000 m$^3$

L/D ratio: 1.3

Stored material: maize ($P_{\text{max}}$=7.5 bar, $K_{\text{st}}$=81 bar m/s)

Reduced explosion pressure: ($P_{\text{red}}$): 0.30 bar

Static activation overpressures ($P_{\text{stat}}$): 0.05 bar
Vent areas required:

7.3 m² according to NFPA 68 (2007)

9.6 m² according to EN 14491 (2006)

Table 4 shows the explosion protection cost (in Euros) and the increment (%) in the total silo price due to the vent panels.

Table 4. Cost of explosion protection by venting in a steel cylindrical silo V=1000 m³.

Maize. $P_{\text{red}}=0.3$ bar. $P_{\text{stat}}=0.05$ bar. $L/D=1.3$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>EN 14491</th>
<th>NFPA 68</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent area (m²)</td>
<td>9.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Number of vent panels (units)</td>
<td>19</td>
<td>14</td>
</tr>
<tr>
<td>Total venting protection cost (€)</td>
<td>4370</td>
<td>3220</td>
</tr>
<tr>
<td>Steel structure cost (€)</td>
<td>13100</td>
<td>13100</td>
</tr>
<tr>
<td>Total cost = structure + protection (€)</td>
<td>17470</td>
<td>16320</td>
</tr>
<tr>
<td>Increment in silo cost due to venting protection (%)</td>
<td>+33%</td>
<td>+25%</td>
</tr>
</tbody>
</table>

4. Conclusions

The vent areas calculated according to EN 14491 were larger than those calculated using NFPA 68 in all cases studied in this work, except when $L/D=1$. The differences were significant for slender silos and when the static activation pressure of the vent devices was low. The minimum explosion prevention cost for standard NFPA 68 was seen at $1 \leq L/D \leq 2$. EN 14491, in contrast, returned the minimum cost for $L/D=1$. This is due to the $L/D$ correction, which is used when $L/D>2$ in NFPA 68, and from $L/D=1$ in EN 14491.
The venting index becomes smaller with increasing silo volume. As a result, the optimum design for a storage facility, taking into account the cost of protection by venting, is represented by a limited number of silos of large volume and with an L/D of 1-2 according to NFPA 68, or of 1 according to EN 14491.

The calculation of vent areas according to these standards, especially EN 14491, may lead to uneconomically viable and impracticably large vents when the volume to protect is large and the enclosure design pressure is low. This would be a quite common scenario for steel cylindrical silos. Further research into dust explosions in large volumes, employing realistic experiments based on real industrial plants, is required in order to determine the most appropriate protection mechanisms.

Acknowledgements

The authors thank the Education Council of the Region of Castilla y León (Spain) and the European Social Fund for their support of this work via grant number LE010B05.

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