



Handbook



Explosion Protection

Version 10.23

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1 Dust and hybrid mixture explosions

Every dust containing carbon is explosive when it is dispersed (Bartknecht 1993). The degree, meaning violence and speed, of a dust explosion depends on the subdivision of the combustible material and therefor on the specific surface area available for the surrounding air. In general, small particles will burn more violently than larger particles of the same material (Eckhoff 2003). Dusts have a lower explosion limit (LEL) and an upper explosion limit (UEL). Normally only the LEL is determined and used for dusts (VDI 2263 part 1 2003). This is because dusts are highly depended on the degree of dispersion (Eckhoff 2003). Dusts can be characterized by the grain size distribution, which gives information about the particle sizes in a dust. Combustible dusts with small median react with a faster pressure rise in an explosion than with higher median (Bartknecht 1993). The LEL of many dusts is between 15-60 kg / m³. The UEL is mostly very high between 2-6 kg/m³ (Bartknecht 1993), but also rarely used when deriving explosion protection measures. In general, there are five requirements for an explosion with dusts, which must be present at the same time and which are shown in figure 3.

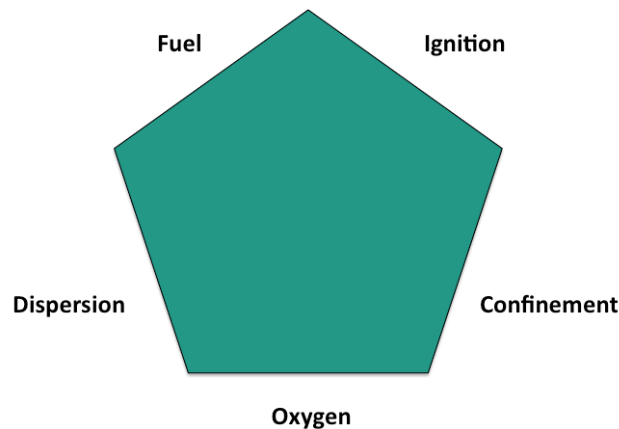


Figure 1 Dust explosion pentagon

If an explosion can occur is highly dependent on five requirements which needs to be met at the same time. Combustible dusts were mentioned as fuel. This fuel needs to be dispersed to get an explosive atmosphere characterized by passing the lower explosion limit (LEL) and being within the explosion limits. Oxygen in a sufficient concentration needs to be present to allow combustion. The limiting oxygen concentration is given by the oxygen concentration where an explosion just not occurs with an ignition-energy of 10 J and an undefined concentration of a dust (Bartknecht 1993). A vessel or other enclosure can act as confinement. The ignition source needs to be effective, means it must be able to

ignite the explosive atmosphere, which is dependent from the ignition energy of the ignition source and the minimum ignition energy (MIE) of the explosive atmosphere (TRBS 2152 2006). Explosive atmosphere focused on dust is defined as a mixture of air and combustible dust under atmospheric conditions where after ignition the combustion process spreads to the mixture (TRBS 2152 2006).

1.1 Safety characteristics of dusts

Safety characteristics of dusts are necessary to assess the hazard and develop and calculate the explosion protection measures defined in the common standards and regulations. There are different safety characteristics for combustible dusts, described in e.g. VDI 2263, EN 14034 or ASTM E 1226 to name a few, which can be used to determine

- Dust explosibility
- Explosible limits
- Maximum explosion pressure $P_{\max}$; maximum rate of pressure rise, K_{St} -value
- Minimum ignition energy (MIE)
- Limiting oxygen concentration
- Minimum ignition temperature (MIT)
- Flammability, Explosibility

Combustible dust was already defined in 1.2 using the definition provided by the NFPA 68. Dusts itself, defined in the VDI 2263, are “fine, dispersed solids of any shape, structure and density having a particle size of less than approximately 500 μm (VDI 2263 1992)”. The safety characteristics K_{St} , $P_{\max}$ and dust explosibility are important for deriving explosion protection measures and are described in the further part. K_{St} , $P_{\max}$ are important because they are used for the calculation approaches in all venting guidelines. Dust explosibility is important because only if a dust is assessed to be explosible further measures regarding explosion protection are necessary.

1.2 Dust explosibility

If an examined dust is going to be assessed as explosible, depends on if there is flame propagation after ignition of the dust cloud in a confined space (VDI 2263 part 1 2003). There are three different test methods described in the regulation referred to three different apparatuses named as the modified Hartmann apparatus and the closed vessel apparatuses 1 m^3 -vessel and 20 l sphere. If using the modified Hartmann apparatus and the dust is assessed as not dust-explosible, the result needs to be verified in one of the closed apparatuses (VDI 2263 part 1 2003).

1.3 K_{St} -value and maximum explosion pressure P_{max}

Explosions are more dangerous when confined. The fast and high-pressure rise cannot escape when confined. Without measures, pressure relief is not possible and explosions cause deformation and destruction of plant components.

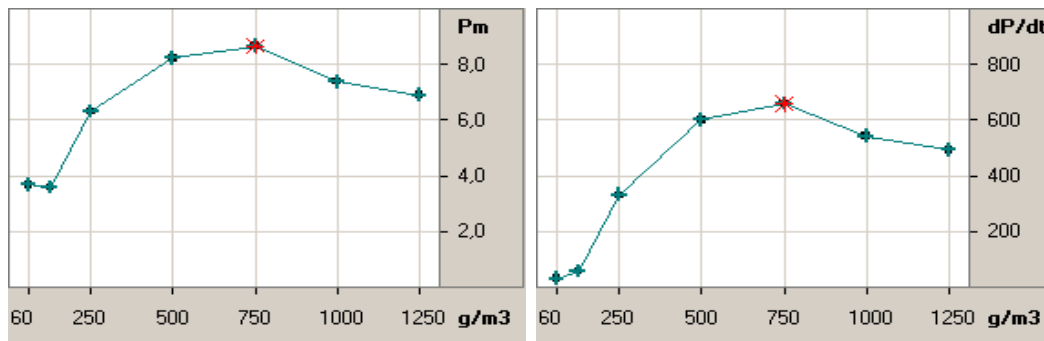


Figure 2 Determination of maximum pressure (p_{max}) and maximum pressure rise (dp/dt) of Niacinamid by using the 20 l sphere with different dust concentrations (Source: KSEP Software)

The K_{St} -value and maximum explosion pressure P_{max} are values for the behaviour of a dust-explosion in a closed system (VDI 2263 part 1 2003). The determination is usually done with the 1 m³ vessel or the 20 l sphere (VDI 2263 part 1 2003). During testing, different dust concentrations per m³ are used to determine the concentration with the highest pressure-rise (dp/dt) and the maximum explosion pressure (P_{max}) (VDI 2263 part 1 2003).

The pressure rise depends on the vessel volume. With increasing volume, the pressure rise decreases (VDI 2263 part 1 2003). Thus, the cubic law is used to calculate the so-called K_{St} -value from the recorded curves of the pressure rise of the test vessel. The K_{St} -value is a dust specific value (VDI 2263 part 1 2003). Depending on the K_{St} -value the dust is associated to a dust explosion class as shown in table 1. According to the regulation NFPA 68, test vessels under 16l are not suitable for the determination of the K_{St} -value (NFPA 68 2018). Varying the test vessel size always can lead to errors (NFPA 68 2018). Figure 4 shows the results of the determination of the maximum pressure and the maximum pressure rise of Niacinamid with different dust concentrations. For the determination the 20l sphere was used and values were calculated by using the cubic law in the program KSEP of the Adolf Kühner AG (Cesana et Al. 2011). Figure 3 and 4 show the three apparatuses used for the determination of safety characteristics. The 20 l sphere and the 1 m³ vessel are also used to determine the explosible limits, the limiting oxygen concentration and minimum ignition energy. Limiting oxygen concentration and minimum ignition energy also can be determined using the modified Hartmann apparatus.

Table 1 Dust explosion class depending on K_{St} -value according to VDI 2263 part 1

K_{St} -value in $\text{bar} \cdot \text{m} \cdot \text{s}^{-1}$	Dust explosion class
> 0 to 200	St 1
> 200 to 300	St 2
> 300	St 3



Figure 3 Modified Hartmann apparatus (Mike 3) (left side) and 20 l sphere (right side) for determination of safety characteristics (Source: REMBE® Research + Technology Center)

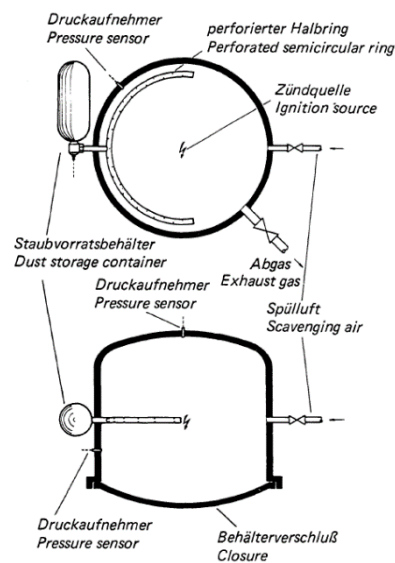


Figure 4 Drawing of 1 m³ vessel (Source: VDI 2263 part 1 2003)

There is a range of different standards and guidelines handling explosion safety / protection in Europe and North America. The ones mostly important for VENT.iNG are shown in table 2.

Table 2 Important guidelines and standard for explosion protection

	European Union	United States of America
Explosion venting	EN 14491:2012 EN 14994:2007 EN 16009:2011 Germany VDI 3673:2002 VDI 2263 In particular VDI 2263 Part 6.1 VDI 2263 Part 7 / 7.1 VDI 2263 Part 8 / 8.1 CEN/TR 16829:2016+AC:2019	NFPA 68:2023 NFPA 61:2019 NFPA 652:2019 NFPA 654:2020
Explosion isolation	EN 14491:2012 EN 15089:2009 EN 16447:2014	NFPA 69:2019
Explosion suppression	EN 14373:2021	NFPA 69:2019

1.4 Hybrid mixtures

Hybrid mixtures are defined as a “mixture of flammable substances with air in different physical states (EN 14491)”. “If the gas and solvent vapour concentration everywhere in the vessel is below 20 % of the lower explosion limit ($LEL_{gas,vapour}$), the hybrid mixture shall be assessed using the explosion indices of the dust present in the mixture. (EN 14491)”. If above the K-values need to be adapted to a higher value.

NFPA 68 defines a hybrid mixture as “explosible heterogenous mixture, comprising gas with suspended solid or liquid particulates, in which the total flammable gas concentration is ≥ 10 % of the lower flammable limit (LFL) and the total suspended particulate concentration is ≥ 10 % of the minimum explosible concentration (MEC) (NFPA 68:2023)”.

With LFL and LEL, different terminology is used in the two standards but meaning the same. However following NFPA 68 the influence of a hybrid mixture already needs to be considered in the calculation from ≥ 10 % LFL / LEL, where EN 14491 allows to still use the dust KSt-values for mixtures containing < 20 % LFL / LEL.

Usually considering a hybrid mixture in the calculations results in an elevated KSt-value of 500 bar*m/s and $P_{max} = 10$ bar. There are ways to determine a more exact value which were described e.g. by Boeck et.al.

2 Venting calculations for dust and hybrid mixture explosions

2.1 Introduction

This chapter handles the sizing equations according to EN 14491:2012, VDI 3673 and NFPA 68:2023, which are used in VENT.iNG. Specific examples are shown to demonstrate how VENT.iNG calculates the vent area sizes and from explosion venting resulting effects like pressures and flames according to the named standards.

2.2 Length / diameter (L/D) calculation according to EN 14491 / NFPA 68

The length / diameter ratio in vent area calculations describes how far the flame can travel before it is vented from an enclosure e.g., Figure 5. An increase of L/D ratio results in an increase of flame propagation and therefor increased resulting explosion pressure in the vented vessel (EN 14491:2012).

The L/D ratio can be calculated using the available equations of EN 14491 and NFPA 68. It is important to know the different approaches of calculation since the results differ between the different standards. Not only differ the L/D calculations, but also the boundary conditions how the calculated value can be used in the equations of the different standards. In the following the different approaches to calculate the L/D according to EN 14491:2012 and NFPA 68:2023 are presented using simple examples.

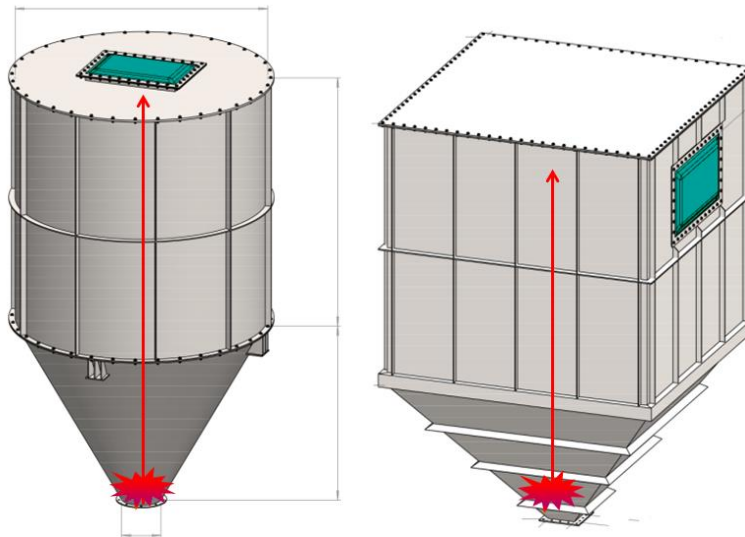
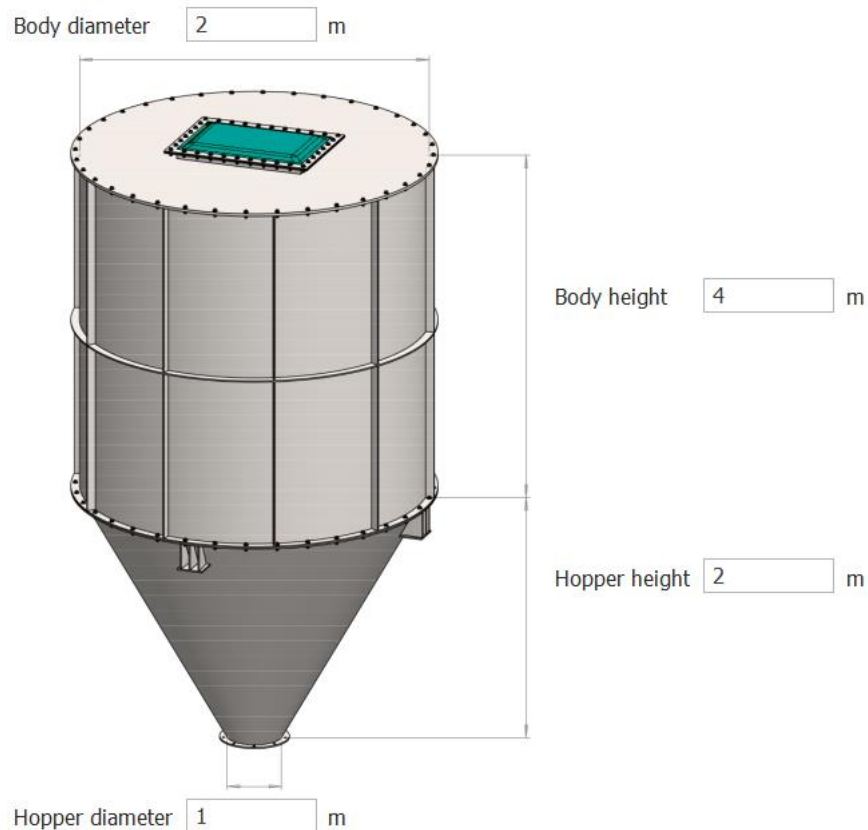


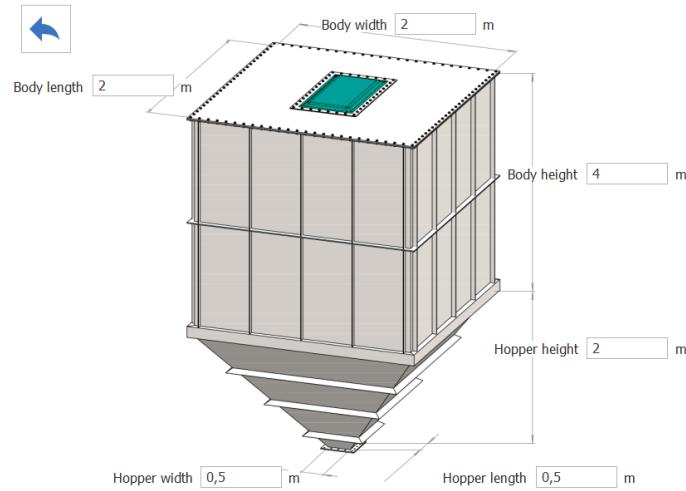
Figure 5 Example for longest flame path in a vessel

2.2.1 Example: Circular vessel with top venting



EN 14491:2012	NFPA 68:2023
$V_{eff/Body} = \frac{\pi \times D^2}{4} \times H = \frac{\pi \times 2^2}{4} \times 4 = 12.56 \text{ m}^3$ $V_{eff/Hopper} = \frac{1}{3} \times V_{Hopper} = 1.22 \text{ m}^3$ $V_{eff/total} = 13.78 \text{ m}^3$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{13.78}{4.67} = 2.95 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 1.93 \text{ m}$ $L/D = \frac{H}{D} = 2.41$	$V_{eff/Body} = \frac{\pi \times D^2}{4} \times H = \frac{\pi \times 2^2}{4} \times 4 = 12.56 \text{ m}^3$ $V_{eff/Hopper} = V_{Hopper} = 1.22 \text{ m}^3$ $V_{eff/total} = 16.23 \text{ m}^3$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{16.23}{6} = 2.7 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 1.86 \text{ m}$ $L/D = \frac{H}{D} = 3.23$

2.2.2 Example: Rectangular vessel with top venting



EN 14491:2012	NFPA 68:2023
$V_{eff/Body} = AxBxH = 16 \text{ m}^3$ $V_{Hopper} = \frac{(Ab + aB + 2(ab + AB)) * h}{6}$ $V_{eff/Hopper} = \frac{1}{3} * V_{Hopper} = 1.166 \text{ m}^3$ $V_{eff/total} = 17.167 \text{ m}^3$ $H_{eff} = H_{Body} + \frac{1}{3} * H_{Hopper} = 4.67$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{17.167}{4.67} = 3.68 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 * A_{eff}}{\pi}} = 2.16 \text{ m}$ $L/D = \frac{H}{D} = 2.16$	$V_{eff/Body} = AxBxH = 16 \text{ m}^3$ $V_{Hopper} = \frac{(Ab + aB + 2(ab + AB)) * h}{6}$ $V_{eff/Hopper} = V_{Hopper} = 3.5 \text{ m}^3$ $V_{eff/total} = 19.5 \text{ m}^3$ $H_{eff} = H_{Body} + H_{Hopper} = 6$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{19.5}{6} = 3.25 \text{ m}^2$ Please note: According to section 6.4.3.6.2 "Where the enclosure and any hopper extension are generally rectangular or square, and the aspect ratio of the largest cross section is between 1 and 1.2, the perimeter D_{eff} shall be permitted to be determined based on a square cross section (NFPA 68:2023)". $D_{eff} = \sqrt{A_{eff}} = 1.8 \text{ m}$ $L/D = \frac{H}{D} = 3.33$ Where $R \geq 1.2$ the following equations are permitted to be used for D_{eff}. $D_1 = \left(\frac{A_{eff}}{R}\right)^{0.5}$ $p = 2 * (R + 1) * D_1$ $D_{eff} = \frac{A_{eff}}{p}$

2.2.3 Example: Circular and rectangular filter with side venting

Calculating the L/D for dust collectors requires some deeper look into the standards, since there are greater differences between the standards itself. Generally, it should be considered to always calculate the L/D via the maximum possible flame path.

Vent panels on dust collectors are usually installed on the lower part of the body section, slightly above the hopper. The maximum value for L/D would result from starting from hopper to the separation of clean air and raw gas side.

EN 14491:2012

Following the Annex C of EN 14491:2012, L/D calculation can be done from the hopper to the upper section of the vent panel when most of the upper volume is occupied by the filter elements and the longest flame path can be considered to be in the lower section of the dust collector. To fulfill this requirement the filter elements should be designed in a way that the enveloping volume requirement of Annex A is fulfilled, given $a \leq r$ for circular filter elements and $a \leq b$ for rectangular filter elements.

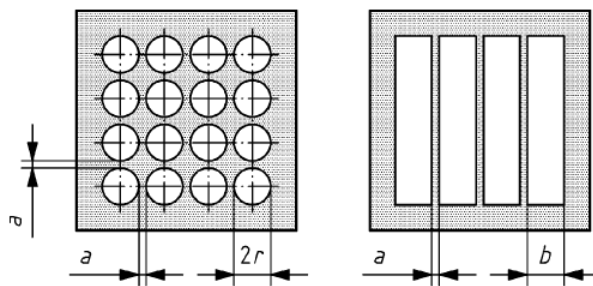


Figure 6 Requirements to deduct the enveloping volume of filter elements (Source: EN 14491:2012)

Per default the calculation in VENT.iNG for dust collectors according to EN 14491:2012 is done, considering the longest flame path is present starting from hopper to upper section of the vent panel. Meaning Annex C and A is considered to be fulfilled.

Note: If the enveloping volume cannot be deducted, the user should assess if the longest flame path is likely given from e.g., top of the filter. In this case the L/D should be calculated by hand.

NFPA 68:2023

The procedure to calculate the L/D for dust collectors is clearly defined.

8.7.1.1 Unlike the general approach of 6.4.3.2 (for other vessels in NFPA 68:2023), the maximum flame length, H , shall be the longest distance, taken on the dirty side of the tube sheet, parallel to the major axis of the enclosure, either horizontal or vertical, and ignoring the location of explosion vents (NFPA 68:2023)".

In particular the results of the L/D calculation for NFPA are more conservative in comparison to EN 14491:2012. The next two examples show a comparison of dust collectors calculated with both standards.

For stretched vessels, where the relief device is only placed on one side and the longest flame path is on the x-axis, the L/D calculation also is done using the x-axis of the vessel. Figure 7 considers this condition in VENT.iNG according to both standards, NFPA and EN.

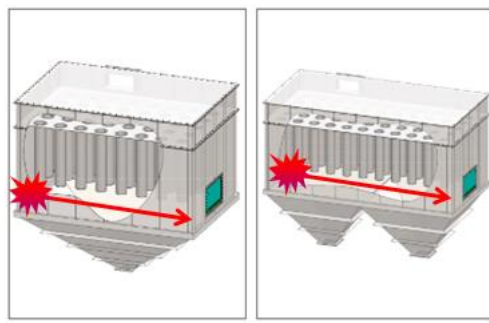
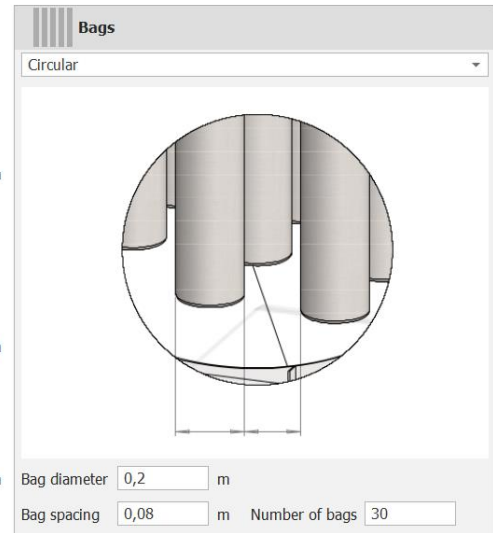
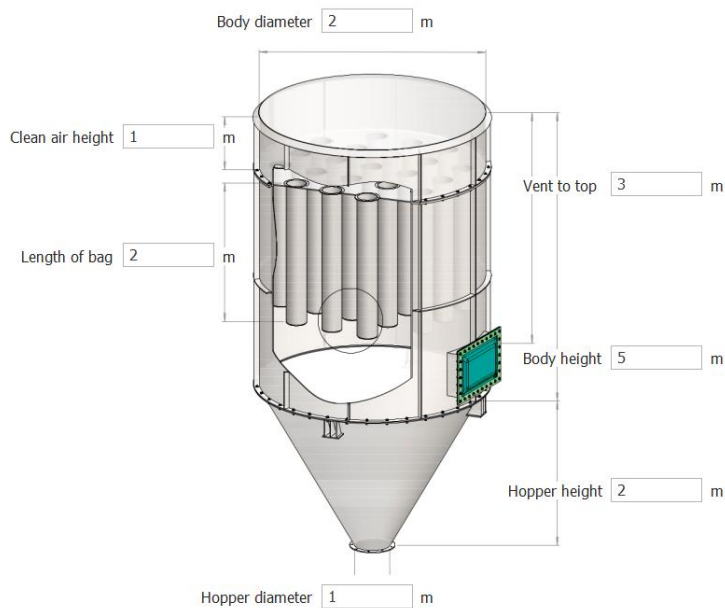
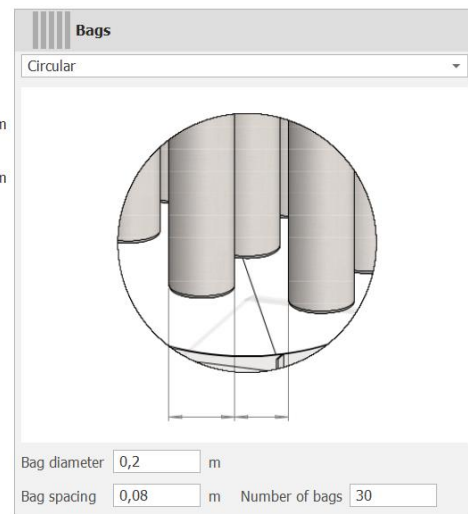
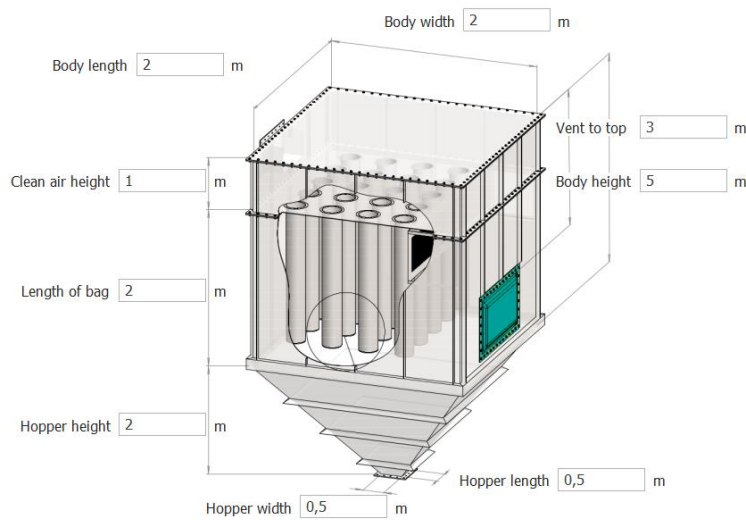


Figure 7 Examples for stretched vessels, with maximum flame length on horizontal axis

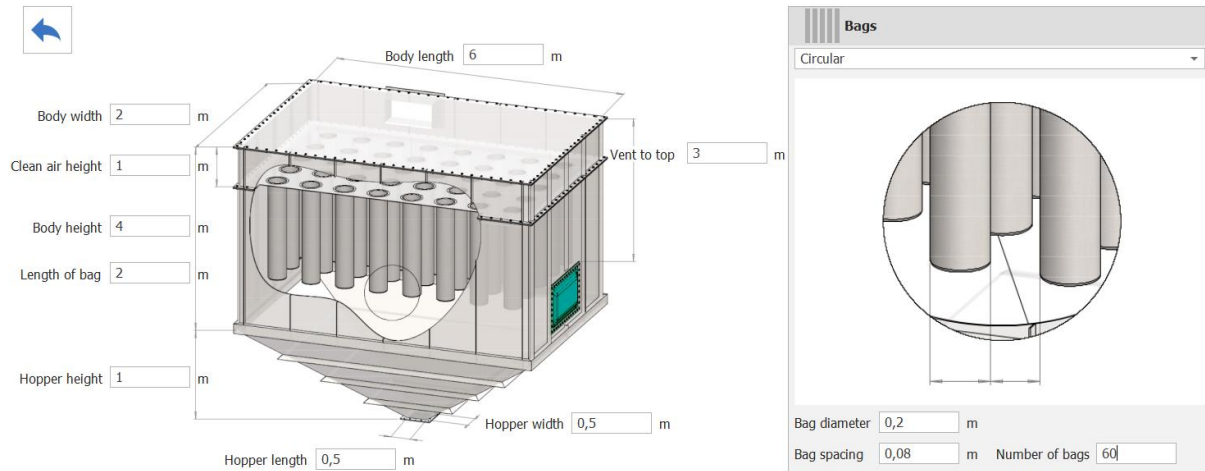


EN 14491:2012	NFPA 68:2023
$V_{eff/Cylinder} = \frac{\pi \times D^2}{4} \times H = \frac{\pi \times 2^2}{4} \times 2 = 6.28 \text{ m}^3$ $V_{effHopperl} = \frac{1}{3} \times V_{Hopper} = 1.22 \text{ m}^3$ $V_{eff/total} = 7.5 \text{ m}^3$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{7.5}{2.67} = 2.814 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 1.89 \text{ m}$ $L/D = \frac{H}{D} = 1.41$ Note: Filter elements are considered as enveloping volume. See EN 14491	$V_{eff/Cylinder} = \frac{\pi \times D^2}{4} \times H = \frac{\pi \times 2^2}{4} \times 4 = 12.56 \text{ m}^3$ $V_{eff/Hopper} = V_{Hopper} = 3.665 \text{ m}^3$ $V_{eff/total} = 16.23 \text{ m}^3$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{16.23}{6} = 2.7 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 1.86 \text{ m}$ $L/D = \frac{H}{D} = 3.23$



EN 14491:2012	NFPA 68:2023
$V_{eff/Body} = A \times B \times H = 2 \times 2 \times 2 = 8 \text{ m}^3$ $V_{eff/Hopper} = \frac{1}{3} \times V_{Hopper} = 1.166 \text{ m}^3$ $V_{eff/total} = 9.167 \text{ m}^3$ $H_{eff} = H_{Body} + \frac{1}{3} \times H_{Hopper} = 2.67$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{9.167}{2.67} = 3.438 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 2.09 \text{ m}$ $L/D = \frac{H}{D} = 1.275$	$V_{eff/Body} = A \times B \times H = 16 \text{ m}^3$ $V_{eff/Hopper} = V_{Hopper} = 3.5 \text{ m}^3$ $V_{eff/total} = 19.5 \text{ m}^3$ $H_{eff} = H_{Body} + H_{Hopper} = 6$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{19.5}{6} = 3.25 \text{ m}^2$ Please note: According to section 6.4.3.6.2 "Where the enclosure and any hopper extension are generally rectangular or square, and the aspect ratio "R" of the largest cross section is between 1 and 1.2, the perimeter D_{eff} shall be permitted to be determined based on a square cross section (NFPA 68:2023)". $D_{eff} = \sqrt{A_{eff}} = 1.8 \text{ m}$ $L/D = \frac{H}{D} = 3.33$ Where R >= 1.2 the following equations are permitted to be used for D_{eff}. $D_1 = \left(\frac{A_{eff}}{R} \right)^{0.5}$ $p = 2 \times (R + 1) \times D_1$ $D_{eff} = \frac{A_{eff}}{p}$

2.2.4 Stretched rectangular dust collector with side venting (venting via the horizontal x-axis)



In this case the calculation of L/D is done by using the horizontal axis of a stretched vessel with venting only on one side as shown in the picture. If venting is applied symmetrically distributed over the vessel please choose another geometry.

EN 14491:2012	NFPA 68:2023
$V_{eff/Body} = A \times B \times H = 2 \times 6 \times 4 = 36 \text{ m}^3$ $V_{eff/Hopper} = \frac{1}{3} \times V_{Hopper} = 1.553 \text{ m}^3$ $V_{eff/total} = 37.553 \text{ m}^3$ $H_{eff} = Body_{width} = 6 \text{ m}$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{37.553}{6} = 6.26 \text{ m}^2$ $D_{eff} = \sqrt{\frac{4 \times A_{eff}}{\pi}} = 2.823 \text{ m}$ $L/D = \frac{H}{D} = 2.125$	$V_{eff/Body} = A \times B \times H = 36 \text{ m}^3$ $V_{eff/Hopper} = V_{Hopper} = 4.75 \text{ m}^3$ $V_{eff/total} = 40.75 \text{ m}^3$ $H_{eff} = Body_{width} = 6 \text{ m}$ $A_{eff} = \frac{V_{eff/total}}{H} = \frac{40.75}{6} = 6.792 \text{ m}^2$ Deff of stretched vessels are calculated according to 6.4.3.6 where “the effective hydraulic diameter, D_{eff}, for the enclosure shall be determined based on the general shape of the enclosure taken normal to the central axis” with $D_{eff} = 4x \frac{A_{eff}}{p} = 4x \frac{6.792}{11} = 2.47$ p = Perimeter taken to the central axis in direction of the vent panel $L/D = \frac{H}{D_{eff}} = 2.43$

3 Venting equations NFPA 68:2023 and EN 14491 for dust explosion venting

3.1 NFPA 68:2023 – Standard on explosion protection by deflagration venting

The standard describes calculations for explosion venting areas in chapter 8 “Venting of deflagrations of dusts and hybrid mixtures”. Equations are valid for L/D-ratios up to six and also permitted up to $L/D \leq 8$ for “top-fed bins, hoppers, and silos, provided the calculated required vent area, after application of all correction factors, does not exceed the enclosure cross section (NFPA 68:2023)”. The standard gives a flowchart (Figure 8) to use the right equations and if necessary additional equations to calculate the vent area depending on the dust characteristics, enclosure volume, pressure, L/D ratio, vent cover area density and vent duct length.

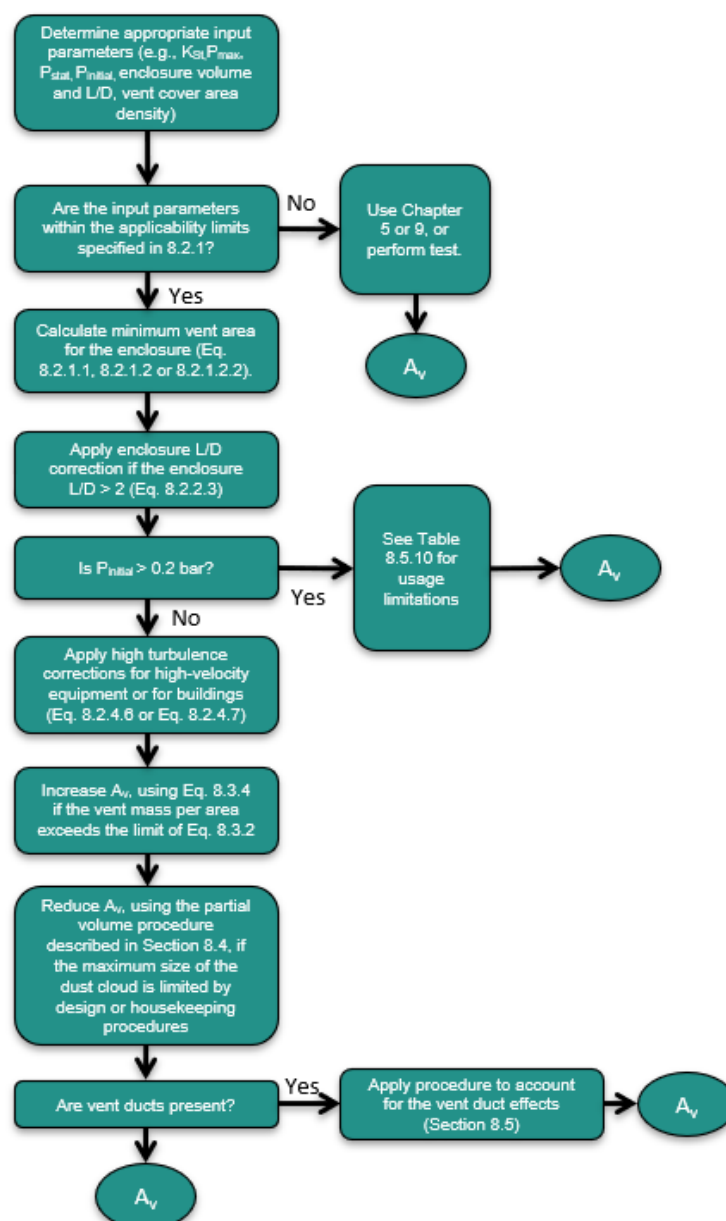


Figure 8 Flowchart for dust explosion vent sizing calculation 8.1.1.4 (Source: NFPA 68:2023)

Low inertia vent closures 8.2

For applications with low-inertia vent closures and near atmospheric initial pressure, the equation in 8.2.1.1 of the standard is given by.

$$A_{v0} = 1 * 10^{-4} * \left(1 + 1.54 * P_{stat}^{\frac{4}{3}}\right) * K_{St} * V^{\frac{3}{4}} * \sqrt{\frac{P_{max}}{P_{red}}} - 1 \quad 8.2.1.2.2$$

where:

A_{v0} = vent area in m^2

P_{stat} = nominal static burst pressure of the vent (bar)

K_{St} = deflagration index ($bar * m * s^{-1}$)

V = enclosure volume (m^3)

P_{max} = maximum pressure of a deflagration (barg)

P_{red} = reduced pressure after deflagration venting (barg)

For applications with low-inertia vent closures and initial pressure < - 0.2 barg or > 0.2 barg, the equation in 8.2.1.2 of the standard is given by

$$A_{v0} = 1 * 10^{-4} * \left(1 + 1.54 * \left(\frac{P_{stat} - P_{initial}}{1 + P_{effective}}\right)^{\frac{4}{3}}\right) * K_{St} * V^{\frac{3}{4}} * \sqrt{\frac{1}{\Pi_{effective}}} - 1 \quad 8.2.1.2$$

where:

$p_{initial}$ = enclosure pressure at moment of ignition (barg)

$$P_{effective} = \frac{1}{3} * P_{initial} \text{ (barg)}$$

$$\Pi_{effective} = \frac{(P_{max} - P_{effective})}{(P_{max}^E - P_{effective})}$$

$$P_{max}^E = \left[\frac{(P_{max} + 1) * (p_{initial} + 1)}{1 \text{ bar} - abs} - 1 \right]$$

maximum pressure of the unvented deflagration at pressure barg

Where the initial pressure is < -0.2 bar, A_{v0} (...) “shall be evaluated over the range between operating pressure and atmospheric pressure and the largest vent area correction applied (NFPA 68:2023).” Also see figure 9.

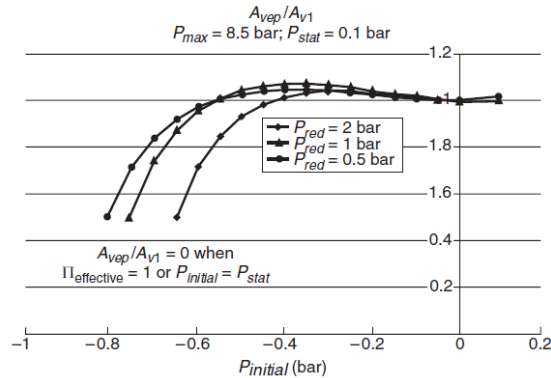


FIGURE A.8.2.1.2.1 Typical Effect of Initial Pressure on Required Vent Area.

Figure 9 Effects of initial pressure on vent area (Source: NFPA 68:2023)

As a simplification it is also permitted to use equation 8.2.1.2.2 instead of 8.2.1.2 in case the initial pressure is < -0.2 bar. $P_{initial}$ is set to 0 in this case. VENT.iNG, however does follow the approach of 8.2.1.2.2.

The use of the equations for A_{v0} in chapter 8 is limited to the following properties.

8.2.1.3

$$5 \text{ bar} \leq P_{max} \leq 12 \text{ bar}$$

$$10 \text{ bar} \cdot \frac{\text{m}}{\text{s}} \leq K_{St} \leq 800 \text{ bar} \cdot \frac{\text{m}}{\text{s}}$$

$$0.1 \text{ m}^3 \leq V \leq 10\,000 \text{ m}^3$$

$$P_{stat} \leq P_{initial} + 0.75 \cdot (1 + P_{effective}) \text{ barg when } P_{initial} > 0.2 \text{ barg}$$

$$P_{stat} < 0.75 \text{ barg when } P_{initial} < 0.2 \text{ barg}$$

Limitations and combination rules for initial pressure > 0.2 barg

$$1.2 \text{ bar-abs} \leq p_{initial} \leq 5 \text{ bar-abs}$$

$$1 \leq L/D \leq 6$$

$$\text{Panel density} \leq M_T \text{ and } \leq 40 \text{ kg/m}^2$$

$$\text{Additional turbulence} < 20 \text{ m/s}$$

No partial volume allowed

No vent ducts allowed

Effect of elevated L/D 8.2.2

These two alternative equations for A_{v0} give the minimum necessary vent area. If L/D is less or equal than two, then $A_{v1} = A_{v0}$. If L/D is above two then

$$A_{v1} = A_{v0} * \left[1 + 0.6 \left(\frac{L}{D} - 2 \right)^{0.75} * \exp \left(-0.95 * \left(\frac{P_{red}}{1 + p_{initial}} \right)^2 \right) \right] \quad 8.2.2.3$$

Where the initial pressure is < 0.2 bar, $p_{initial}$ shall be set to 0 in A_{v1} .

Effects of additional turbulence 8.2.4

After calculating A_{v1} the standard asks for determination of the effects of additional turbulence in section 8.2.4. This turbulence factor can be calculated for a) axial air velocity and b) circumferential (i.e., tangential) air velocity.

a) Average axial gas velocity

$$v_{axial} = \frac{Q}{A} \quad 8.2.4.1$$

Where:

$$v_{axial} = \text{average axial air velocity} \left(\frac{m}{s} \right)$$

$$Q = \text{volumetric air flow rate} \left(\frac{m^3}{s} \right)$$

$$A = \text{average cross – sectional area of the flow path} (m^2)$$

b) Circumferential (i.e. tangential) air velocity

$$v_{tan} = 0.5 * v_{tan,max}$$

Once the values for air velocities inside the equipment are derived by an experienced professional engineer, the values are compared to the boundary of 20 m/s. If either v_{tan} or v_{axial} are below 20 m/s then $A_{v2} = A_{v1}$. If above 20 m/s, A_{v2} is calculated by.

$$A_{v2} = \left[1 + \frac{\max(v_{axial}, v_{tan}) - 20}{36} * 0.7 \right] * A_{v1} \quad 8.2.4.6$$

Vent area for buildings 8.2.4.7

- Will be added later -

Effects of panel inertia 8.3

Explanation: The panel inertia can have a negative influence on the venting process. Mostly inertia “free” vent covers like light aluminum foil will not cause any influence on the venting process. NFPA gives guidance on how to account the panel mass M into the calculation and check if a correction factor needs to be applied. Experience shows that the panel mass has a high influence on the vent area calculation for small volumes, low K_{St} and low p_{red} .

For cases where the panel mass is $\leq 40 \text{ kg/m}^2$ the threshold mass can be calculated by

$$M_T = \left[6.67 * (p_{red}^{0.2}) * (n^{0.3}) * \left(\frac{V}{K_{St}^{0.5}} \right) \right]^{1.67} \quad 8.3.2$$

where:

$$M_T = \text{threshold mass} \left(\frac{\text{kg}}{\text{m}^2} \right)$$

p_{red} = reduced explosion pressure after deflagration venting (barg)

n = number of panels

V = volume (m^3)

K_{St} = deflagration index $\left(\text{bar} * \frac{\text{m}}{\text{s}} \right)$

If $M \leq M_T$, A_{v3} is equal to A_{v2}

If $M > M_T$ the vent area A_{v3} shall be calculated by

$$A_{v3} = F_{SH} \left[1 + (0.0075) * M^{0.6} * \left(\frac{K_{St}^{0.5}}{n^{0.3} * V * p_{red}^{0.2}} \right) * A_{v2} \right] \quad 8.3.4$$

where

$F_{SH} = 1$ for translating panels or 1.1 for hinged panels

M = mass of vent panel $\left(\frac{\text{kg}}{\text{m}^2} \right)$

A_{v2} = vent area calculated by 8.2.5.6, Equation 8.2.4.6, or Equation 8.2.4.7, as applicable

if $K_{St} < 75 \text{ bar} * \frac{\text{m}}{\text{s}}$; $K_{St} = 75$ shall be used in Equation 8.3.4

If the panel mass is $> 40 \text{ kg/m}^2$, see Annex G of NFPA 68:2023 for further instructions.

Limitations and combination rules

$P_{initial} \leq 1.2 \text{ bar-abs}$

$1 \leq L/D \leq 6$

Vent ducts allowed

Turbulence correction allowed

Partial volume correction allowed

Elevated pressure not allowed

Effect of partial volume 8.4

Explanation: For equipment like spray dryers, a risk assessment can show an only partial involvement of the equipment volume in the explosion. This is related to a mostly wet part in the upper section of the dryer, where nonsolvent liquids like milk is sprayed into the spray dryer. It is allowed to include this assessment via a partial volume calculation, which will lead to reduced vent areas. Partial volume approach cannot be used for dryers, which use recirculation of already dry product. If applying partial volume, venting should be applied in the section of the dryer which is considered to be the driest. The

volume fill fraction X_R needs to be determined and then used in equation 8.4.1

$$X_R = \frac{M_e / (V_{enc} - V_{solid})}{c_r} \quad 8.4.1$$

Where

M_e = total mass of combustible dust that could be suspended inside the enclosure

V_{enc} = enclosure volume (m^3)

V_{solid} = volume of solid objects (m^3)

$c_r = 0.5 * c_w$

c_w = worst case dust concentration (g/m^3)

C_w is based upon $(dp/dt)_{max}$ dust concentration determined by using ASTM E 1226, Standard Test Method for Explosibility of Dust Clouds.

If c_w is not available, 200 g/m^3 shall be permitted to be used in c_r .

$$A_{v4} = A_{v3} * X_R^{-\frac{1}{3}} * \sqrt{\frac{X_R - \Pi}{1 - \Pi}} \quad 8.4.3$$

Where:

A_{v4} = vent area for partial volume deflagration

A_{v3} = vent area for full volume deflagration as determined from Equation 8.3.4 or from 8.3.6

$$X_R = \text{fill fraction} > \Pi$$

$$\Pi = \frac{p_{red}}{p_{max}}$$

If $X_R \leq \Pi$ deflagration venting is not required.

Where $X_R = 1$ and therefor no partial volume is used, A_{v4} shall be equal to A_{v3} .

Limitations and combination rules

$p_{initial} \leq 1.2$ bar-abs

$1 \leq L/D \leq 6$

Panel density ≤ 40 kg/m²

Turbulence correction allowed

Vent ducts allowed

Elevated pressure not allowed

Building partial volumes 8.4.3

- Will be added later -

Effect of vent ducts 8.5

Vent ducts increase the reduced explosion pressure $p_{red,max}$ in the protected equipment. The length of the vent duct plays a significant role for the calculation. The pressure increases with increasing length of the vent duct.

The influence of the vent duct on the required vent area can be calculated using in iterative process given by the following equations

$$A_{vf} = A_{v4} * (1 * 1.18 * E_1^{0.8} * E_2^{0.4}) * \sqrt{\frac{K}{K_0}} \quad 8.5.1 \text{ a}$$

$$E_1 = \frac{A_{vf} * L_{duct}}{V} \quad 8.5.1 \text{ b}$$

$$E_2 = \frac{A_{vf} * 10^4}{\left(1 + 1.54 * p_{stat}^{\frac{4}{3}}\right) * K_{St} * V^{\frac{4}{3}}} \quad 8.5.1 \text{ c}$$

$$K = K_{inlet} + \frac{f_D * L_{duct}}{D_h} K_{elbows} + K_{outlet} + \dots \quad 8.5.1 \text{ d}$$

$$f_D = \frac{1}{\left(1.14 - 2 * \log_{10}\left(\frac{\varepsilon}{D_h}\right)\right)}^2 \quad \text{A.8.5 c}$$

where:

A_{vf} = vent area including vent duct correction (m²)

A_{v4} = vent area after partial volume correction (m²)

K = overall resistance coefficient of vent duct

$K_0 = 1.5$, fixed resistance coefficient taken from test configurations to derive above equations

L_{duct} = Length of vent duct, including centerline length through elbow and fittings (m)

f_D = D'Arcy friction factor for fully turbulent flow

D_h = hydraulic diameter of vent duct (m)

ε = effective roughness of duct (mm),

typically between 0.0015 mm

– 0.046 mm. Based on the frequent use of corroded ducts in tests a value of 0.26 is mostly used

The following shall apply.

- In case two vent areas result from the calculation, the smaller one shall be used 8.5.2
- In cases where there is no solution, either the pred needs to be increased or the vent duct shortened
- The explosion panel shall be placed on the equipment and not on the end of the duct
- The initial pressure needs to be less than 0.2 bar-g
- The vent duct cross section shall not vary more than 10 %
- Elbows, rain covers, and bird screens are allowed if they are considered in the calculation via the resistance coefficient K. (Annex A of NFPA 68:2023)
- The maximum vent ducts length which shall be allowed to use is given by

$$L_{eff} \leq \min\left(\frac{10,000 \cdot D}{K_{St}}, \frac{11,000}{K_{St}}\right) \quad 8.5.9$$

where:

$$L_{eff} = \min(L_{Duct}, L_{dusty})$$

$$L_{dusty} = (P_{max} - p_{red,max}) * \frac{V}{A}$$

Limitations and combination rules

$P_{initial} \leq 1.2$ bar-abs

$1 \leq L/D \leq 6$

Panel density ≤ 40 kg/m²

Turbulence correction allowed

Partial volume correction allowed

Elevated pressure not allowed

3.2 EN 14491:2012 - Dust explosion venting protective systems

The content, for isolated enclosure explosion venting, of the EN standard, does not differ much from the content of VDI 3673 part 1. The size of the explosion venting area depends on the dust characteristics, size and geometry of the enclosure and on turbulence, concentration and dispersion of the dust. The equations in the standard are derived for calculation of vent sizes in atmospheres with optimal dust concentration and turbulent condition. If special dust cloud conditions apply for example because of pneumatic conveying systems, different equations need to be considered according to 5.3 of the EN standard.

In general, the following applies

- Initial process conditions
 - absolute pressure 1.1 bar,
 - oxygen concentration ≤ 21 %
 - temperature between -20 °C and 60 °C

All the following equations are also valid for vessels with integrated filter, required the filter elements enveloping volume does not exceed 5 % of the vessel volume. The pressure resistance of the integrated filter elements needs to be at least the same as the equipment. If the filter is separate from the main equipment, it requires separate venting and explosion isolation.

Homogenous dust cloud approach 5.2

Vent area A:

for

$$0.1 \text{ bar overpressure} \leq p_{red,max} < 1.5 \text{ bar overpressure}$$

$$A = B (1 + C * \log L/D)$$

$$B = (3.264 * 10^{-5} * p_{max} * K_{St} * p_{red,max}^{-0.569} + 0.27 * (p_{stat} - 0.1) * p_{red,max}^{-0.5}) * V^{0.753}$$

$$C = (-4.305 * \log(p_{red,max}) + 0.785)$$

for

$$1.5 \text{ bar overpressure} \leq p_{red,max} \leq 2.0 \text{ bar overpressure}$$

$$A = B$$

The equations are valid for following boundary conditions.

- Enclosure volume $0.1 \text{ m}^3 \leq V \leq 10.000 \text{ m}^3$
- Static activation pressure $0.1 \text{ bar} \leq p_{\text{stat}} \leq 1 \text{ bar}$
- Maximum reduced overpressure $0.1 \text{ bar} < p_{\text{red,max}} \leq 2 \text{ bar}$
- K_{St} and maximum explosion overpressure
 - $5 \text{ bar} \leq p_{\text{max}} \leq 10 \text{ bar}$ for $10 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1} \leq K_{\text{St}} \leq 300 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1}$
 - $5 \text{ bar} \leq p_{\text{max}} \leq 12 \text{ bar}$ for $300 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1} \leq K_{\text{St}} \leq 800 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1}$
- Length to diameter ratio $1 \leq L/D \leq 20$

Special dust cloud conditions 5.3

Extensive research has been conducted on explosion venting of inhomogeneous dust cloud explosions (Arnold et al. 2001). Inhomogeneous dust clouds are present during pneumatic filling of silos and equipment, resulting in lower explosion pressures and therefor in smaller vent areas compared to the homogenous dust cloud approach described above.

For **axial pneumatic filling** where **one** filling line is near the center of the vessel following equations can be applied for calculating the vent area.

For vessel heights $\leq 10 \text{ m}$

$$A = X \left(1 + Y * \log \left(\frac{L}{D} \right) \right)$$

For vessel heights $> 10 \text{ m}$

$$A = 0.1 * L * X * \left(1 + Y * \log \left(\frac{L}{D} \right) \right)$$

With

$$X = \left(\frac{1}{D_z} * (8.6 * \log(p_{\text{redmax}}) - 6) - 5.5 * \log(p_{\text{redmax}}) + 3.7 \right) * 0.011 * K_{\text{St}} * D_F$$

$$Y = 1.0715 * p_{\text{redmax}}^{-1.27}$$

Where

$$D_F = \text{diameter of axial inlet pipe} \leq 0.3 \text{ m}$$

$$D_z = \text{effective diameter of vessel} = \sqrt[3]{\frac{4 * V}{\pi}}$$



- Enclosure volume	$10 \text{ m}^3 \leq V \leq 250 \text{ m}^3$
- Static activation pressure	$p_{\text{stat}} \leq 0.1 \text{ bar}$
- Maximum reduced overpressure	$0.1 \text{ bar} < p_{\text{red,max}} \leq 2 \text{ bar}$
- Maximum explosion overpressure	$p_{\text{max}} \leq 9 \text{ bar for}$ $50 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1} \leq K_{\text{St}} \leq 300 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1}$
- Length to diameter ratio	$1 \leq L/D \leq 20$
- Air conveying velocity	$v_i = 30 \text{ m/s}$
- Maximum volume flow rate	$2.500 \text{ m}^3/\text{h}$

For **tangential pneumatic filling** with **one** filling pipe applied to the top tangential perimeter of the equipment, following equations can be applied to calculate the vent area.

$$A = X \left(1 + Y * \log \left(\frac{L}{D} \right) \right)$$

$$X = \left(\frac{1}{D_z} * \left(\left(\frac{8.6}{k} \right) * \log(p_{\text{red,max}}) \right) - \left(\frac{K_{\text{St}}}{44} \right) - 0.513 \right) - \left(\frac{5.5}{k} \right) * \log(p_{\text{red,max}}) + \left(\frac{K_{\text{St}}}{69} \right) + 0.191$$

$$* 0.011 * K_{\text{St}} * D_F$$

$$Y = 0.166 * e^{\frac{K_{\text{St}}}{129}} * p_{\text{red,max}}^{\frac{-1.27}{k}}$$

With

- $K = 1$ for $0.1 \text{ bar} \leq p_{\text{red,max}} \leq 1.0 \text{ bar}$
- $K = 2$ for $1.0 \text{ bar} < p_{\text{red,max}} \leq 1.7 \text{ bar}$

Where

- Enclosure volume	$10 \text{ m}^3 \leq V \leq 120 \text{ m}^3$
- Static activation pressure	$p_{\text{stat}} \leq 0.1 \text{ bar}$
- Maximum reduced overpressure	$0.1 \text{ bar} < p_{\text{red,max}} \leq 1.7 \text{ bar}$
- Maximum explosion overpressure	$p_{\text{max}} \leq 9 \text{ bar for}$ $100 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1} \leq K_{\text{St}} \leq 220 \text{ bar} \cdot \text{m} \cdot \text{s}^{-1}$
- Length to diameter ratio	$1 \leq L/D \leq 5$
- Air conveying velocity	$v_i = 30 \text{ m/s}$
- Maximum volume flow rate	$2500 \text{ m}^3/\text{h}$

For **free fall filling** via rotary valves or screw conveyors, equations of axial filling can be used to calculate the vent area.

Where

- Maximum feed rate 8,000 kg/h
- Equivalent diameter of feed opening $D_F \leq 0.3 \text{ m}$

Effect of vent ducts 5.6

Vent ducts increase the reduced explosion pressure $p_{red,max}$ in the protected equipment. The length of the vent duct plays a significant role for the calculation. The pressure increases with increasing length of the vent duct.

The influence of the vent duct on the $p_{red,max}$ can be calculated by the following equation applied to the results of 5.3 and 5.4.

$$p'_{red,max,L/D=1} = p_{red,max} * (1 + 17.3 * (A * V^{-0.753})^{1.6} * l$$

with

$p'_{red,max}$ = Maximum reduced explosion pressure in the equipment with vent duct (barg)

A = calculated vent area without vent duct (m^2)

V = volume of vented equipment (m^3)

l = length of vent duct (m)

Where

- Enclosure volume $0.1 \text{ m}^3 \leq V \leq 10,000 \text{ m}^3$
- Length / diameter ratio vent duct $0.5 < l/d \leq 20$
- Length of vent duct $l \leq 10 \text{ m}$
- Static activation pressure $0.1 < p_{stat} \leq 0.2 \text{ bar}$
- Maximum reduced overpressure with duct $p'_{red,max} \leq 2 \text{ bar}$
- Maximum reduced overpressure w/o vent duct $0.1 \text{ bar} < p_{red,max} \leq 2 \text{ bar}$
- K_{St} and maximum explosion overpressure $5 \text{ bar} \leq p_{max} \leq 12 \text{ bar}$ for
 $10 \text{ bar} \cdot m \cdot s^{-1} \leq K_{St} \leq 400 \text{ bar} \cdot m \cdot s^{-1}$

 $5 \text{ bar} \leq p_{max} \leq 12 \text{ bar}$ for

organic dusts
 $300 \text{ bar} \cdot m \cdot s^{-1} \leq K_{St} \leq 800 \text{ bar} \cdot m \cdot s^{-1}$

metal dust
 $\leq 200 \text{ bar} \cdot m \cdot s^{-1}$

Research has shown a stagnating effect of vent ducts on the $p'_{red,max}$ for organic dusts once the explosion reaches the velocity of sound in the vent duct if the following condition is met

$$l = l_s = 4.564 * p_{red,max}^{-0.37}$$

Vent ducts with a length over l_s do not have an additional effect on $p'_{red,max}$ for organic dust. This approach does not apply to metal dusts.

For elongated vessels, with higher L/D and venting into the elongated direction of the vessel, the equation above may overpredict the effects of the duct on $p'_{red,max}$. Research has shown that for such cases the $p'_{red,max}$ is likely to be lower. EN 14491:2012 allows to use published and validated research data to calculate an alternative $p'_{red,max}$.

A methodical approach is given in VDI 3673 part 1 to account for this effect. For vessels where venting is applied on top of the elongated vessel and $L/D = 6$ following equations can be used. VENT.iNG automatically applies this correction if top venting is selected in the position section. If this approach is not wanted, the position "Side" needs to be selected to solely follow EN 14491:2012.

$$p'_{red,max,L/D=6} = (0.0586 * l + 1.023) * p'_{red,max}^{(0.981-0.0197*l)}$$

For all other cases where

- Length / diameter ratio of vessel $1 < L/D < 6$
- Length of vent duct $l \leq l_s$
- Maximum reduced overpressure w/o vent duct $p_{red,max} \leq 2 \text{ bar}$

A linear interpolation is applied using below equation given by

$$p'_{red,max,L/D=X} = 0.2 * (C_1 - C_2) * \left(1 - \frac{L}{D}\right) + C_1$$

With

$$C_1 = p'_{red,max,L/D=1}$$

$$C_2 = p'_{red,max,L/D=6}$$

3.3 Flame length calculations

Flame lengths of explosion venting can be calculated using the following equations. Looking at the equations they are very similar to each other but used for rather different purposes.

EN 14491:2012	NFPA 68:2023
Flame length - Horizontal venting $L_F \approx 10 * V^{\frac{1}{3}}$ Flame length - Vertical venting $L_F \approx 8 * V^{\frac{1}{3}}$ with $L_F = \text{flame length (m)}$ $V = \text{enclosure volume (m}^3\text{)}$ for: $0.1 \text{ m}^3 < V < 10,000 \text{ m}^3$ $0.1 < p_{\text{stat}} \leq 0.2 \text{ bar}$ $0.1 \text{ bar} < p_{\text{red,max}} \leq 2 \text{ bar}$ $5 \text{ bar} < P_{\text{max}} \leq 10 \text{ bar}$ $10 \text{ bar*m/s} \leq K_{\text{St}} \leq 300 \text{ bar*m/s}$ $L/D < 2$ Flame width – Horizontal and vertical venting $W_F \approx 2.8 * V^{\frac{1}{3}}$ $W_F = \text{flame width (m)}$ for: $K_{\text{St}} \leq 200 \text{ bar*m/s}$	Flame length – Metal dust explosions $L_F \approx 10 * \frac{V^{\frac{1}{3}}}{n} \quad [6.8.3]$ Flame length – Organic dust explosions $L_F \approx 8 * \frac{V^{\frac{1}{3}}}{n} \quad [6.8.3]$ with $L_F = \text{flame length and width (m)}$ $V = \text{enclosure volume (m}^3\text{)}$ $n = \text{number of independent vents, with}$ $\text{vent centers spaced at least}$ $4 \text{ times the hydraulic diameter of the largest vent}$ For $0.3 \text{ m}^3 < V < 10,000 \text{ m}^3$ $p_{\text{stat}} \leq 0.1 \text{ bar}$ $p_{\text{red,max}} \leq 1 \text{ bar}$ $K_{\text{St}} \leq 300 \text{ bar*m/s}$ Note: Independent vents are defined “6.8.4.1 For vents located at a single elevation and spaced around the circumference of a cylindrical vessel, the normal to the adjacent vents shall be separated by at least 60 degrees or 4 hydraulic diameters of the largest vent. 6.8.4.2 Vents located on different sides of a rectangular enclosure shall be considered independent, 6.8.4.3* For vents located along the axis of a cylindrical vessel or on die same side of a rectangular enclosure, the center of the vents shall be separated by at least four times the hydraulic diameter of the largest vent. N 6.S.4.4 Vents that do not meet the requirements of 6.8.4 are allowed but shall not be counted separately to calculate n in 6.8.2 or 6.8.3”
The maximum flame length shall be limited to 60 m in all cases and both standards	

EN 14491:2012

NFPA 68:2023

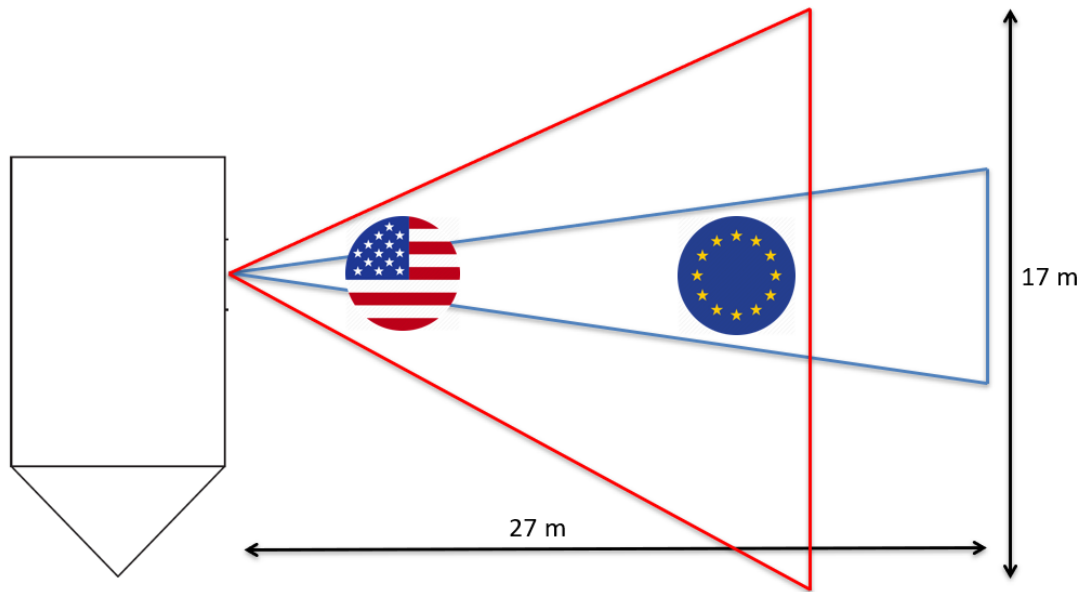


Figure 10 Example for 20 m³ silo with venting of organic dust on one side of the silo

EN 14491:2012

NFPA 68:2023

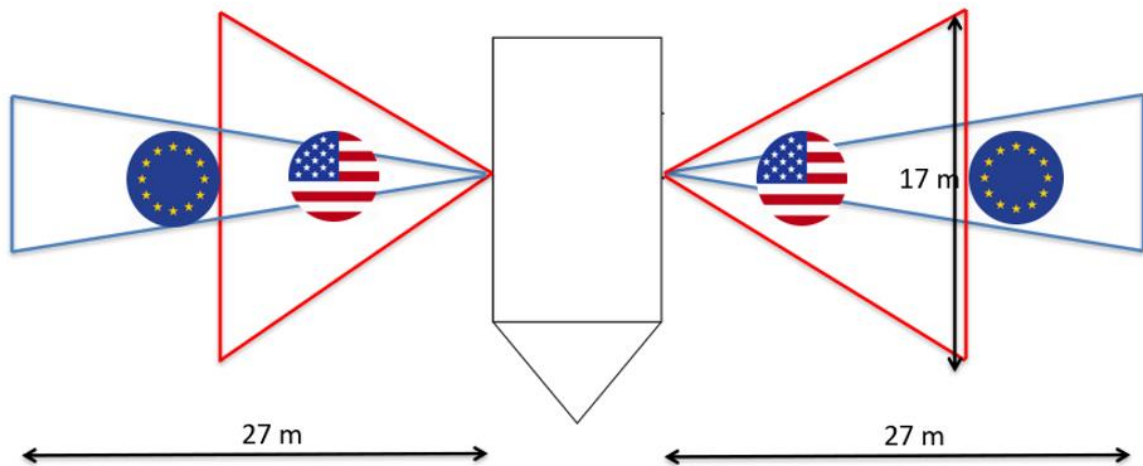


Figure 11 Example for 20 m³ silo with venting of organic dust on two symmetrical sides of the silo

3.4 Calculation of forces / external pressures

Maximum external pressures and forces can be calculated as follows

EN 14491:2012	NFPA 68:2023
Maximum external pressures $p_{ext,max} = 0.2 * p_{red,max} * A^{0.1} * V^{0.18}$ Where $p_{ext,max} = \text{maximum external pressure (bar)}$ Distance of maximum external pressure given by $R_s = 0.25 * L_F$ $L_F = \text{flame length (m)}$ For distances larger R_s, external pressures are given by $p_{ext,r} = p_{ext,max} * \left(\frac{R_s}{r}\right)^{1.5}$ (used in VENT.iNG) Where $r = \text{distance to vent opening (m)}$ Distance dependent maximum explosion over pressure at a certain location $p_{ext,r} = 1.24 * p_{red,max} * \left(\frac{D}{r}\right)^{1.35} / \left(1 + \left(\frac{\alpha}{56}\right)^2\right)$ Where $D = \text{hydraulic diameter of vent (m)}$ $\alpha = \text{direction towards the vent opening}$ $\alpha = 0^\circ \text{ in front of the vent}$ $\alpha = 90^\circ \text{ to the side of the vent}$ for: $0.1 \text{ m}^3 < V \leq 250 \text{ m}^3$ $p_{stat} \leq 0.1 \text{ bar}$ $0.1 \text{ bar} < p_{red,max} \leq 1.0 \text{ bar}$ $r > R_s$ $P_{max} \leq 9 \text{ bar}$ $K_{St} \leq 200 \text{ bar*m/s}$ $L/D < 2$	Maximum external pressures $p_{ext,max} = 0.2 * p_{red,max} * A^{0.1} * V^{0.18} [6.8.7]$ Where $p_{ext,max} = \text{maximum external pressure (bar)}$ Distance dependent maximum explosion over pressure $p_{ext,r} = p_{ext,max} * \left(\frac{\alpha * L_F}{r}\right) [b]$ Where $L_F = \text{Flame length (m)}$ $\alpha = 0.2 \text{ for horizontal vents}$ $\alpha = 0.25 \text{ for vertical vents (upward)}$ $r = \text{distance to vent opening (m)}$ for: $0.3 \text{ m}^3 < V \leq 10,000 \text{ m}^3$ $P_{red,max} \leq 1.0 \text{ bar}$ $p_{stat} \leq 0.1 \text{ bar}$ $0.1 \text{ bar} < p_{red,max} \leq 1.0 \text{ bar}$ $P_{max} \leq 9 \text{ bar}$ $K_{St} \leq 200 \text{ bar*m/s}$

3.5 Effects of explosion pressures on humans and buildings

Explosions can have a massive impact on buildings and the human body table 3 gives an overview about this. EN 16009:2011 being the European certification standard for flameless venting states, that pressures above 70 mbar are unacceptable where people are present. Smaller pressures can already have an impact on the building and cause indirect hazards for people by e.g., debris.

Table 3 Effect of overpressures on structures and the human body. Partly reproduced from: Zipf R., Cashdollar K. Effects of blast pressure on structures and the human body

Peak overpressure in bar	Peak overpressure in psi	Effect on structures	Effect on human body
0.069	1	Window glass shatters	Light injuries from fragments occur
0.137	2	Moderate damage to houses (windows and doors blown out and severe damage to roofs)	People injured by flying glass and debris
0.206	3	Residential structures collapse	Serious injuries are common, fatalities may occur
0.344	5	Most buildings collapse	Injuries are universal, fatalities are widespread
0.689	10	Reinforced concrete buildings are severely damaged or demolished	Most people are killed
1.378	20	Heavily built concrete buildings are severely damaged or demolished	Fatalities approach 100%

Note: Most fatalities related to explosions in the industry result from debris.

4 Explosion isolation of dusts and hybrid mixtures

4.1 Introduction

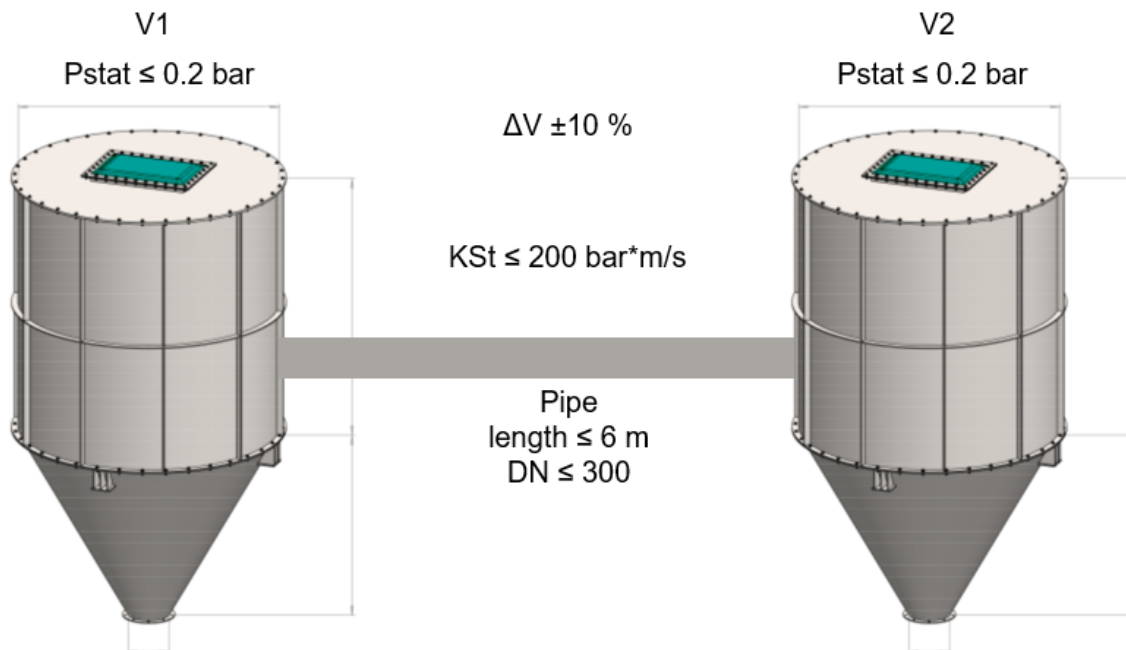
Process equipment is usually connected with pipes, which are used to convey or aspirate product from one equipment to another. It has been proven that explosions initiated in one equipment, will propagate into connected equipment via these pipes. In most cases propagation is not only limited to an ignition of an explosive atmosphere in the connected equipment only but will be severely stronger due to flame jet ignition and pressure piling effects in the duct (Hattwig et al. 2003, Bartknecht 1996). Therefore explosion isolation is mandatory, limiting the effects of the explosion to the vessel it initially started in and preventing a much stronger secondary explosion in connected process equipment. Explosion isolation systems should be certified according to EN 15089:2008 and for the North American market additionally fulfill the requirements of NFPA 69:2019.

There are certain cases where explosion isolation between two vessels can be waived if both vessels fulfill certain requirements. If applying these exceptions, an explosion in the secondary vessel is accepted. These exceptions differ between the standards and are defined as follows.

4.2 EN 14491:2012 - Dust explosion venting protective systems

If explosion isolation of dust explosions can be waived according to the European standard is described in EN 14491:2012 chapter 5.4.

Chapter 5.4.2 a.



Isolation EN 14491:2012

Vessel 1		Vessel 2	
11 m³	V (Volume)	11 m³	
1	L/D (Length / Diameter)	1	
0,5 bar	Pred,max (Reduced explosion pressure)	0,5 bar	
0,1 bar	Pstat (Static activation pressure)	0,1 bar	
9 bar	Pmax (Maximum explosion pressure)	9 bar	
200 bar * m/s	KSt (Maximum explosion pressure rise)	200 bar * m/s	
0,6 bar	Pes (Vessel strength)	0,6 bar	
0,53 m²	Vent area (Geometric)	0,53 m²	
Duct diameter 0,2 m			
Duct length 5 m			

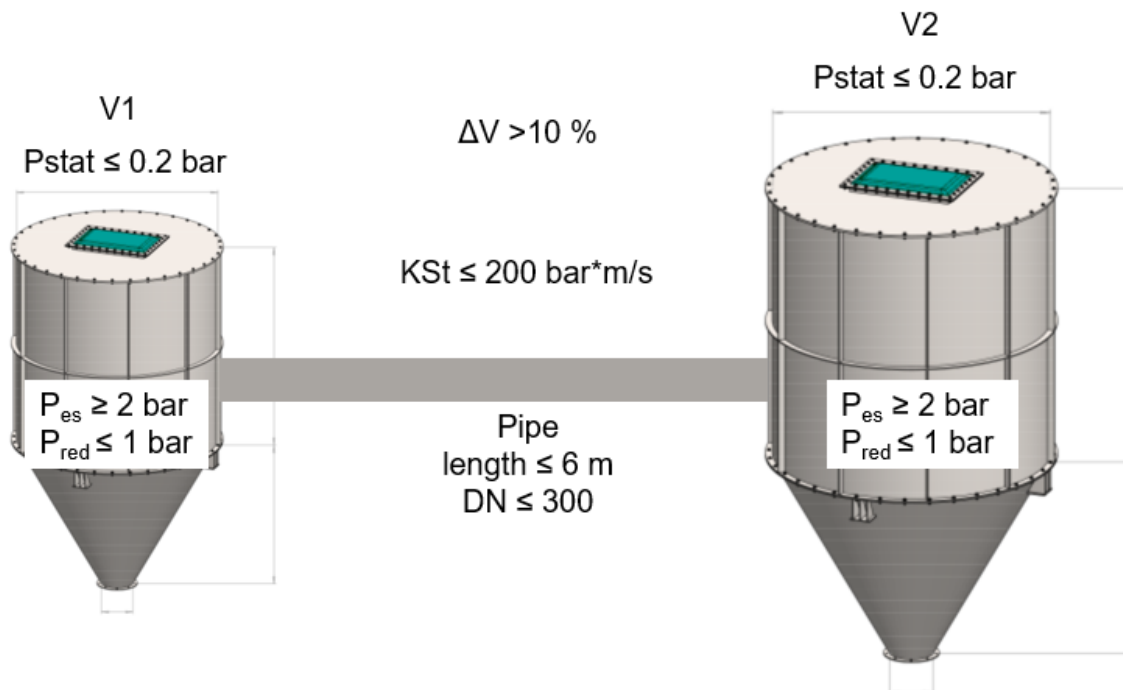
Result: Explosion isolation not required according to chapter 5.4.2 a)

Area correction: N/A

Boundary conditions: KSt ≤ 200 bar·m/s
Length of duct ≤ 6 m
Diameter of duct ≤ 0.3 m
Volume difference between vessel smaller ±10 %
Pstat < 0.2 bar

Figure 12 Exception for explosion isolation following 5.4.2 a

Chapter 5.4.2 b.



Note: "If it is not possible to vent the enclosure with the smaller volume (..), it shall be designed for the maximum deflagration pressure P_{max} and the vent area of the larger vessel shall be doubled (EN 14491:2012, NFPA 68:2023)".

Isolation EN 14491:2012

Vessel 1

13	m³	V (Volume)	11	m³
1		L/D (Length / Diameter)	1	
0,5	bar	Pred,max (Reduced explosion pressure)	0,5	bar
0,1	bar	Pstat (Static activation pressure)	0,1	bar
9	bar	Pmax (Maximum explosion pressure)	9	bar
200	bar * m/s	KSt (Maximum explosion pressure rise)	200	bar * m/s
2	bar	Pes (Vessel strength)	2	bar
0,53	m²	Vent area (Geometric)	0,54	m²

Duct diameter 0,2 m
Duct length 5 m

Copy values

+

-

x

=

Explosion isolation required?

Result:

Area correction:

Boundary conditions:

Explosion isolation not required according to chapter 5.4.2b)

N/A

KSt <= 200 bar*m/s
Length of duct <= 6 m
Diameter of duct <= 0.3 m
Pred,max <= 0.5 bar
Pes >= 2 bar for both vessels
Pstat < 0.2 bar

?

Figure 13 Exception for explosion isolation following 5.4.2 b

Chapter 5.4.3 a.

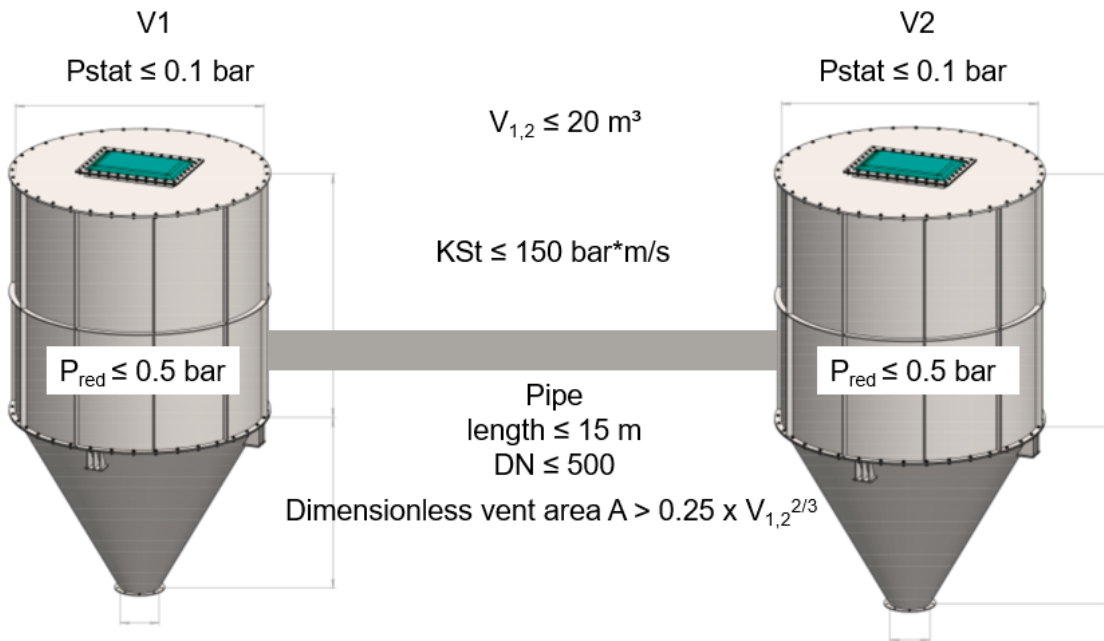


Figure 14 Exception for explosion isolation following 5.4.3 a

Note: The dimensionless vent area needs to be equal for V1 and V2.

5.4.3 b.

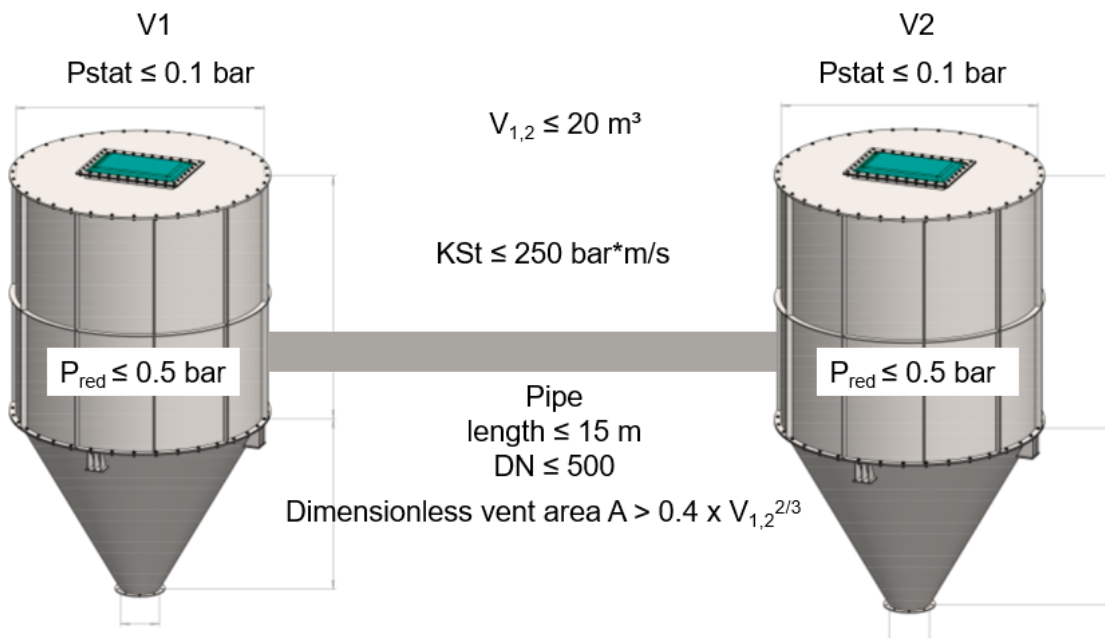


Figure 15 Exception for explosion isolation following 5.4.3 b

Note: The dimensionless vent area needs to be equal for V1 and V2.

Where none of these exceptions are met explosion isolation is mandatory. Explosion isolation can be achieved by either passive or active systems.

4.3 NFPA 68:2023 – Standard on explosion protection by deflagration venting

Chapter 8.11.1

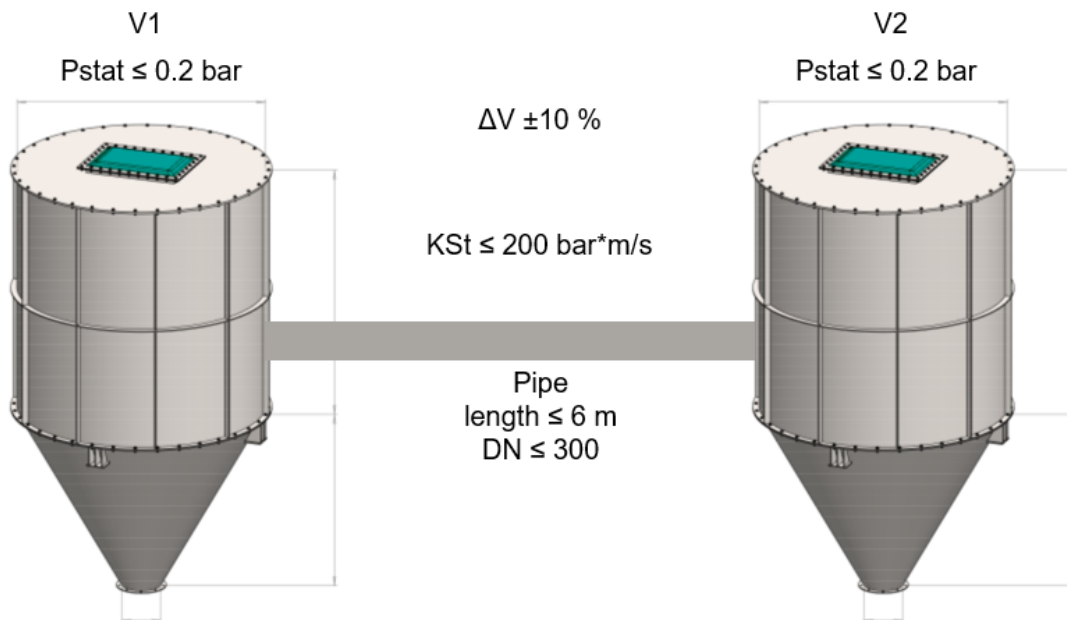


Figure 16 Exception for explosion isolation following 8.11.1

Chapter 8.11.1

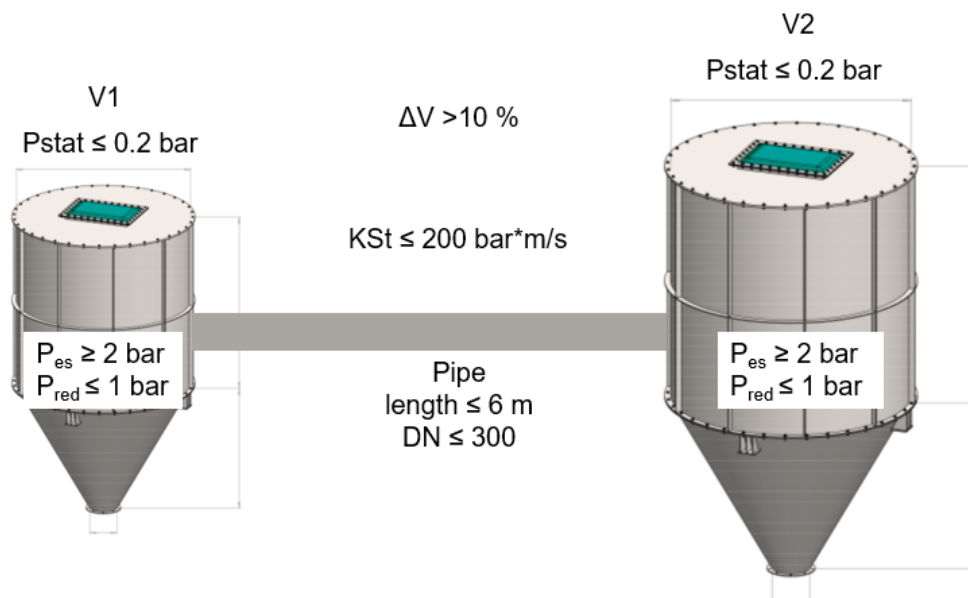


Figure 17 Exception for explosion isolation following 8.11.1

Note: "If it is not possible to vent the enclosure with the smaller volume(..), it shall be designed for the maximum deflagration pressure P_{max} and the vent area of the larger vessel shall be doubled (EN 14491:2012, NFPA 68:2023)".

5 Explosion pressures in pipes

5.1 Introduction

As already mentioned in explosion isolation chapter, pipes will lead to pressure piling effects and flame jet ignition in connected equipment. For certain boundary conditions it is possible to calculate the increasing pressure in the pipe according to EN 14491:2012

5.2 EN 14491:2012 - Dust explosion venting protective systems

Chapter 5 of EN 14491:2012 gives following equations to calculate the length of the pipe (L) a certain pressure can be expected. The $p_{red,max}$ in the vessel calculated by the venting equations should not exceed 0.5 bar. The equations are valid for straight pipes and pipe diameters $200 \geq DN \geq 600$.

For

$KSt \leq 100 \text{ bar} \cdot \text{m/s}$; limited to L/D of pipe ≤ 100

$$L = D * [324.8 * (1 - e^{-0.1072 * pL})]$$

$100 < KSt \leq 200 \text{ bar} \cdot \text{m/s}$; limited to L/D of pipe ≤ 50

$$L = D * [83.57 - 81.99 * e^{-0.1640 * pL}]$$

$200 < KSt \leq 300 \text{ bar} \cdot \text{m/s}$; limited to L/D of pipe ≤ 50

$$L = D * [63.76 - 62.42 * e^{-0.1484 * pL}]$$

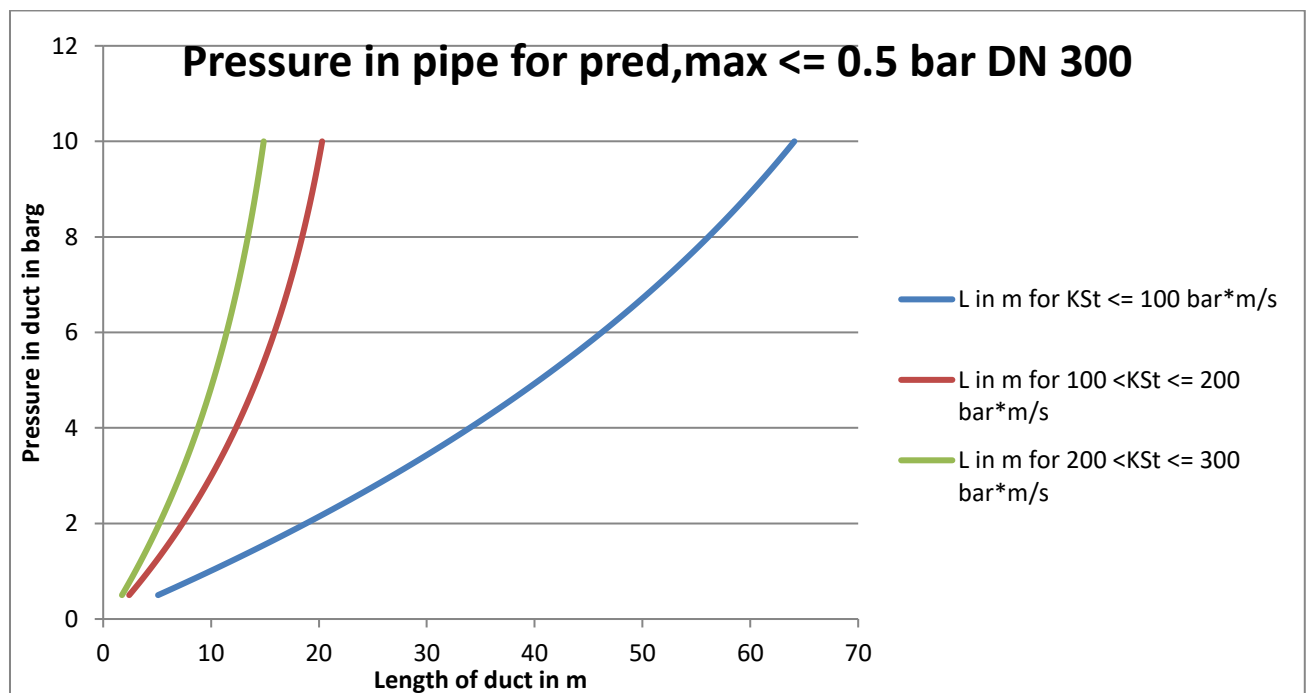


Figure 18 Pressure in pipes for $p_{red,max} \leq 0.5 \text{ bar}$ and DN 300

5.3 NFPA 68:2023 – Standard on explosion protection by deflagration venting

- NFPA does not apply this approach –

6 Dust case studies / Example calculations using EN and NFPA in VENT.iNG

6.1 Silos

A silo storing granulated sugar shall be calculated using the following parameters.

P_{max}: 9 barg

*K_{St}: 190 bar*m/s*

P_{red,max}: 1 bar

P_{stat}: 0.1 bar

Panel mass: 10 kg/m²; E_f (Efficiency of venting device) 100 % according to EN 14797:2007

No vent duct applied

No solvents / No hybrid mixture

Filling method:

Option 1: Not known.

Option 2: Axial filling; Height of fall: 5 m; Diameter of conveying tube: 0.1 m;

conveying speed: 19 m/s; Airflow: 2100 m³/h

Dimensions:

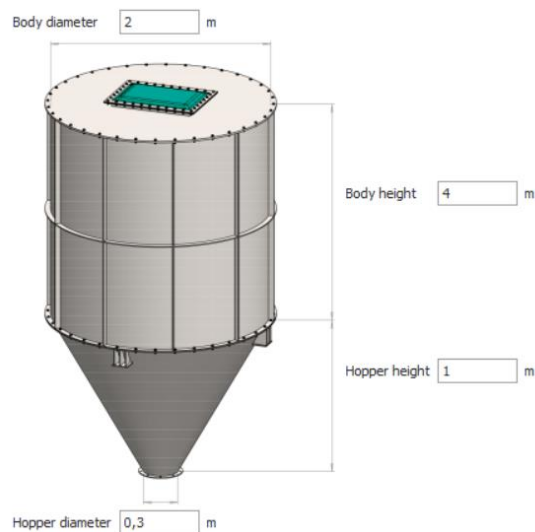
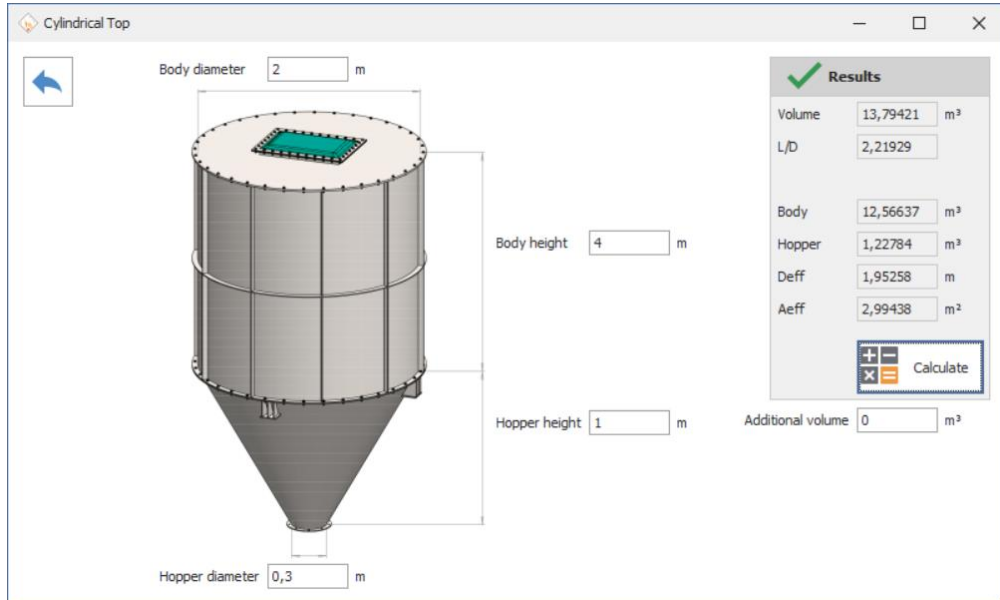


Figure 19 Example silo dimensions

6.1.1 EN 14491:2012 - Dust explosion venting protective systems

The L/D calculation is applied using 1/3 of the conical hopper and the full length of the cylindrical part resulting in an L/D of 2.22. Figure 20.



Cylindrical Top

Body diameter: 2 m

Body height: 4 m

Hopper height: 1 m

Hopper diameter: 0,3 m

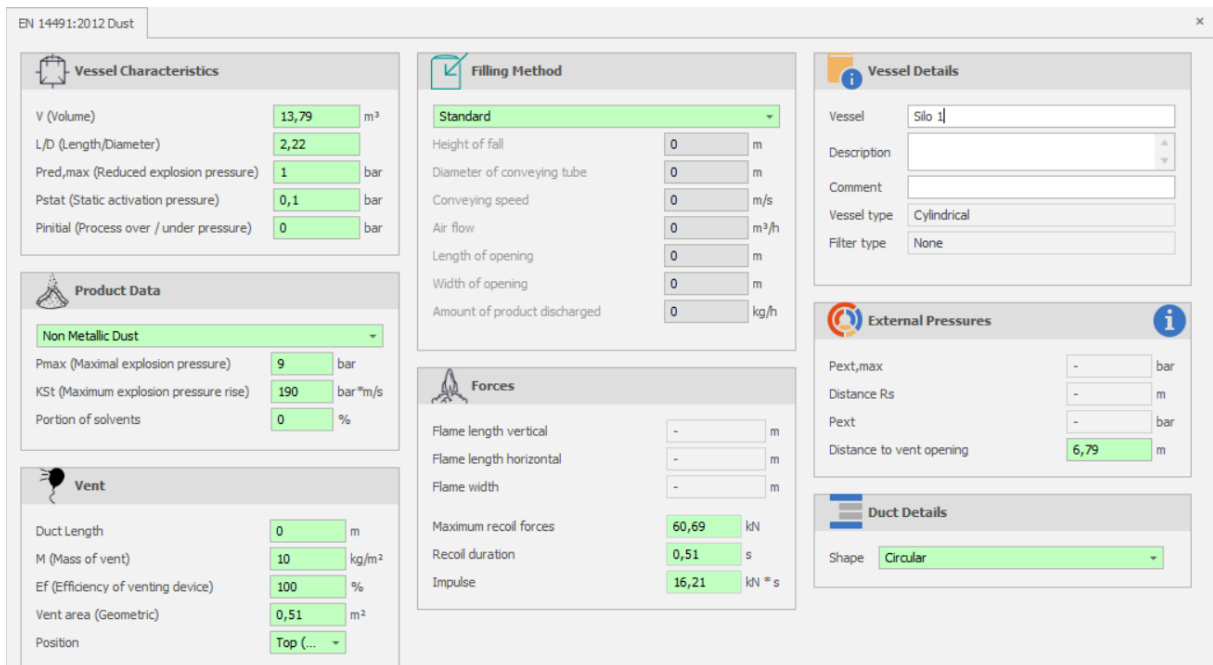
Results

Volume	13,79421 m³
L/D	2,21929
Body	12,56637 m³
Hopper	1,22784 m³
Deff	1,95258 m
Aeff	2,99438 m²
Additional volume	0 m³

Calculate

Figure 20 L/D calculation for example silo

Applying the vent area calculation according to EN 14491:2012 results in 0.51 m² with the EN standard equations / homogenous dust cloud.



EN 14491:2012 Dust

Vessel Characteristics

V (Volume)	13,79 m³
L/D (Length/Diameter)	2,22
Pred,max (Reduced explosion pressure)	1 bar
Pstat (Static activation pressure)	0,1 bar
Pinitia (Process over / under pressure)	0 bar

Product Data

Non Metallic Dust

Pmax (Maximal explosion pressure)	9 bar
KSt (Maximum explosion pressure rise)	190 bar*m/s
Portion of solvents	0 %

Vent

Duct Length	0 m
M (Mass of vent)	10 kg/m²
Ef (Efficiency of venting device)	100 %
Vent area (Geometric)	0,51 m²
Position	Top

Filling Method

Standard

Height of fall	0 m
Diameter of conveying tube	0 m
Conveying speed	0 m/s
Air flow	0 m³/h
Length of opening	0 m
Width of opening	0 m
Amount of product discharged	0 kg/h

Forces

Flame length vertical	- m
Flame length horizontal	- m
Flame width	- m
Maximum recoil forces	60,69 kN
Recoil duration	0,51 s
Impulse	16,21 kN * s

Vessel Details

Vessel: Silo 1

Description:

Comment:

Vessel type: Cylindrical

Filter type: None

External Pressures

Pext,max	- bar
Distance Rs	- m
Pext	- bar
Distance to vent opening	6,79 m

Duct Details

Shape: Circular

Figure 21 Vent area calculation for homogenous dust cloud approach acc. to EN 14491:2012

EN 14491:2012 Dust

Vessel Characteristics		Filling Method		Vessel Details	
V (Volume)	13,79 m ³	Height of fall	5 m	Vessel	Silo 1 / Axial filling
L/D (Length/Diameter)	2,22	Diameter of conveying tube	0,1 m	Description	
Pred,max (Reduced explosion pressure)	1 bar	Conveying speed	19 m/s	Comment	
Pstat (Static activation pressure)	0,1 bar	Air flow	2100 m ³ /h	Vessel type	Cylindrical
Pinitial (Process over / under pressure)	0 bar	Length of opening	0 m	Filter type	None
		Width of opening	0 m		
		Amount of product discharged	0 kg/h		

Product Data		Forces		External Pressures	
Non Metallic Dust		Flame length vertical	- m	Pext,max	- bar
Pmax (Maximal explosion pressure)	9 bar	Flame length horizontal	- m	Distance Rs	- m
KSt (Maximum explosion pressure rise)	190 bar * m/s	Flame width	- m	Pext	- bar
Portion of solvents	0 %	Maximum recoil forces	47,6 kN	Distance to vent opening	6,79 m
		Recoil duration	0,66 s		
		Impulse	16,21 kN * s		

Vent		Duct Details	
Duct Length	0 m	Shape	Circular
M (Mass of vent)	10 kg/m ²		
Ef (Efficiency of venting device)	100 %		
Vent area (Geometric)	0,4 m ²		
Position	Top (...)		

Figure 22 Vent area calculation for inhomogenous dust cloud approach acc. to EN 14491:2012

6.1.2 NFPA 68:2023 – Standard on explosion protection by deflagration venting

The L/D calculation is applied using the full conical hopper and the full length of the cylindrical part resulting in an L/D of 2.67. Figure 23.

Cylindrical Top

Body diameter m

Body height m

Hopper height m

Hopper diameter m

Results

Volume m³

L/D

Body m³

Hopper m³

Deff m

Aeff m²

Additional volume m³

Calculate

Figure 23 L/D calculation for example silo

NFPA 68:2018 Dust

Vessel Characteristics

V (Volume) m³

L/D (Length/Diameter)

Pred,max (Reduced explosion pressure) bar

Pstat (Static activation pressure) bar

Pinitia (Process over / under pressure) bar

FSH

Duct Details

Kinlet

E (E)

Kelbows

Koutlet

Dh m

Shape

Vessel Details

Vessel

Description

Comment

Vessel type

Filter type

Product Data

Pmax (Maximal explosion pressure) bar

KSt (Max. explosion pressure rise) bar * m/s

Portion of solvents %

External Pressures

Alpha

Pext,max bar

Distance to vent opening m

Forces

Flame length m

Flame width m

Maximum recoil forces kN

Recoil duration s

Impulse kN * s

Effects Of Additional Turbulence

Average gas velocity m/s

Vent

Duct Length m

M (Mass of vent) kg/m²

Amount of Vents

Vent area (Geometric) m²

Partial Volume Correction

XR

Figure 24 Vent area calculation acc. to NFPA 68:2023

6.2 Dust collectors

A dust collector aspirating cornstarch dust shall be calculated using the following input parameters.

P_{max}: 9 barg

*K_{St}: 200 bar*m/s*

P_{red,max}: 0.5 bar

P_{stat}: 0.1 bar

Panel mass: 10 kg/m²; E_f (Efficiency of venting device) 100 % according to EN 14797:2007

No vent duct applied

No solvents / No hybrid mixture

Filling method: Not applicable for dust collector

We are using the same geometry example, which already has been used in chapter 2.2.3 to show the L/D calculation for dust collectors.

6.2.1 EN 14491:2012 - Dust explosion venting protective systems

The L/D calculation is applied using the distance from hopper to upper section of the vent panel. The filter elements are deducted as enveloping volume, fulfilling Annex A and C of EN 14491:2012. The clean air side of the dust collector and the enveloping volume of the filter bags are deducted from the volume, which is used for the calculation of the vent area. (Figure 19, 20).

Enveloping volume of filter elements

Due to different distribution options, the calculation of the enveloping volume in VENT.iNG follows an idealized approach, which might differ from the real physical enveloping volume. Depending on the vessel geometry and filter element distribution the real value can vary. Thus, this value should be cross-checked by hand-calculation, considering the real filter layout.

Table 4 Idealized approach for enveloping volume calculation

Enveloping volume circular filter elements	Enveloping volume rectangular filter elements
$V_{\text{Bags,Envelope}} = [d+a]^2 \times l \times N_B$ d =diameter of filter elements [m] a =distance between filter elements [m] l =length of filter elements [m] N_B =Number of filter elements "bags"	$V_{\text{Bags,Envelope}} = [N_B \times w + (N_B-1) \times a] \times d \times l$ d =depth of filter elements [m] w =width of filter elements [m] a =distance between filter elements [m] l =length of filter elements [m] N_B =Number of filter elements "bags"

Cylindrical Body, Filter

Body diameter: 2 m

Clean air height: 1 m

Length of bag: 2 m

Vent to top: 3 m

Body height: 5 m

Hopper height: 2 m

Hopper diameter: 1 m

Bags

Circular

Bag diameter: 0,2 m

Bag spacing: 0,08 m

Number of bags: 30

Results

Volume: 11,52756 m³

L/D: 1,40872

Body: 12,56637 m³

Hopper: 3,66519 m³

Bag: 4,704 m³

Deff: 1,89297 m

Aeff: 2,81434 m²

Additional volume: 0 m³

Calculate

Figure 25 L/D and volume calculation for a dust collector following EN 14491:2012

The equations used in this vent area calculation are described in chapter 3.1. The equations for external pressures / forces and flames are described in chapter 3.3 and 3.4.

EN 14491:2012 Dust

Vessel Characteristics

V (Volume): 11,53 m³

L/D (Length/Diameter): 1,41

Pred,max (Reduced explosion pressure): 0,5 bar

Pstat (Static activation pressure): 0,1 bar

Pinitial (Process over / under pressure): 0 bar

Product Data

Non Metallic Dust

Pmax (Maximal explosion pressure): 9 bar

KSt (Maximum explosion pressure rise): 200 bar * m/s

Portion of solvents: 0 %

Vent

Duct Length: 0 m

M (Mass of vent): 10 kg/m²

Ef (Efficiency of venting device): 100 %

Vent area (Geometric): 0,72 m²

Position: Side

Filling Method

Standard

Height of fall: 0 m

Diameter of conveying tube: 0 m

Conveying speed: 0 m/s

Air flow: 0 m³/h

Length of opening: 0 m

Width of opening: 0 m

Amount of product discharged: 0 kg/h

Forces

Flame length vertical: 18,07 m

Flame length horizontal: 22,59 m

Flame width: 6,33 m

Maximum recoil forces: 42,84 kN

Recoil duration: 0,64 s

Impulse: 14,27 kN * s

Vessel Details

Vessel: Dust collector / filter

Description:

Comment:

Vessel type: Cylindrical Filter

Filter type: Circular

External Pressures

Pext,max: 0,15 bar

Distance Rs: 5,65 m

Pext: 0,15 bar

Distance to vent opening: 5,65 m

Duct Details

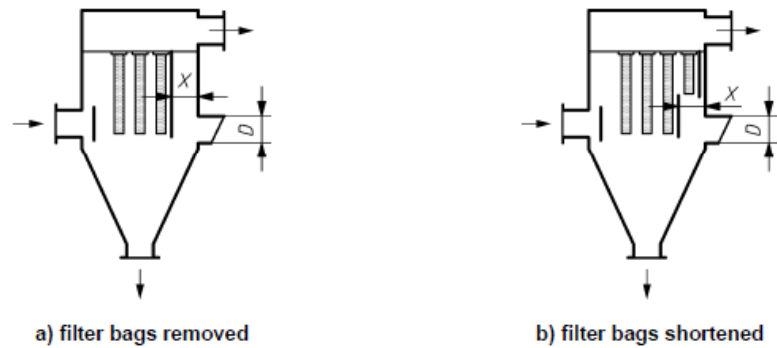
Shape: Circular

Figure 26 Vent area calculation of dust collector following EN 14491:2012

Important key facts:

- Clean air side needs to be essentially free of combustible material
 - If combustible material is present on the clean air side, it needs to be vented independently
- Separation plate between clean and raw gas side needs to withstand pred,max
- Preferred position of vent panel is below the filter elements
 - If not possible, filter elements need to be cut to allow a free flow. Filter elements possibly obstructing the vent opening should be hold in place by bars. (Figure 21)

- Volume of filter elements can be deducted from explosive volume.
 - In some cases, the enveloping volume can be deducted. Table 4



Key

- X distance between the first arrays of filter elements and the venting device
- D diameter of venting device

Figure A.2 — Filter elements in front of the venting device

Figure 27 Arrangement of vent panel to avoid blocking by filter elements (Source: EN 14491:2012)

6.2.2 NFPA 68:2023 – Standard on explosion protection by deflagration venting

As explained in chapter 2.2.3, NFPA 68:2023 calculates the L/D up to the separation plate of the filter, which separates clean air side and raw gas side. The position of the vent panel itself is neglected in the calculation resulting in a rather high L/D. Volume of filter elements are not deducted from the total volume considered for the vent area calculation. This leads to rather high vent areas in direct comparison to the result from EN 14491:2012 as calculated in Figure 20.

Equal to EN 14491:2012, NFPA 86:2018 requires excluding the presence of combustible material on the clean air side. In case dust, is present on the clean air side or the material handled is a hybrid mixture, the clean air side shall be vented independently.

Cylindrical Body, Filter

Body diameter: 2 m

Clean air height: 1 m

Length of bag: 2 m

Vent to top: 3 m

Body height: 5 m

Hopper height: 2 m

Hopper diameter: 1 m

Bags

Circular

Bag diameter: 0,2 m

Bag spacing: 0,08 m

Number of bags: 30

Results

Volume: 16,23156 m³

L/D: 3,2329

Body: 12,56637 m³

Hopper: 3,66519 m³

Deff: 1,85592 m

Aeff: 2,70526 m²

Additional volume: 0 m³

Calculate

Figure 28 L/D and volume calculation for a dust collector following NFPA 68:2023

EN 14491:2012 Dust NFPA 68:2018 Dust

Vessel Characteristics		Duct Details		Vessel Details	
V (Volume)	16,23 m ³	Kinlet	Flush (1,5)	Vessel	Dust collector / filter
L/D (Length/Diameter)	3,23	E (€)	0,26	Description	
Pred,max (Reduced explosion pressure)	0,5 bar	Kelbows	0	Comment	
Pstat (Static activation pressure)	0,1 bar	Koutlet	0	Vessel type	Cylindrical Filter
Pinitial (Process over / under pressure)	0 bar	Dh	0 m	Filter type	Circular
FSH	1,1	Shape	Circular		

Product Data		External Pressures		Effects Of Additional Turbulence	
Non Metallic Dust		Alpha	Vertical (...)	No influence	
Pmax (Maximal explosion pressure)	9 bar	Pext,max	- bar	Average gas velocity	
KSt (Max. explosion pressure rise)	200 bar * m/s	Distance to vent opening	- m	0 m/s	
Portion of solvents	0 %				

Vent		Forces	
Duct Length	0 m	Flame length	- m
M (Mass of vent)	10 kg/m ²	Flame width	- m
Amount of Vents	1	Maximum recoil forces	66,6 kN
Vent area (Geometric)	1,11 m ²	Recoil duration	0,27 s
		Impulse	9,24 kN * s

Partial Volume Correction	
Partial Volume Correction	No
XR	0

Figure 29 Vent area calculation of dust collector following NFPA 68:2023

The equations used in this vent area calculation are described in chapter 3.1. The equations for external pressures / forces and flames are described in chapter 3.3 and 3.4.

Important key facts:

- Clean air side needs to be essentially free of combustible material
 - If combustible material is present on the clean air side, it needs to be vented independently
 - If a hybrid mixture is present the clean air side shall be vented according to chapter 7 of NFPA 68:2023.
- Separation plate between clean and raw gas side needs to withstand pred,max
- Preferred position of vent panel is below the filter elements
 - If not possible, filter elements need to be cut to allow a free flow. Filter elements possibly obstructing the vent opening should be hold in place by bars.
- If flexible filter elements are blocking the opening, the calculated vent area shall be increased by 25 %

7 Venting equations NFPA 68:2023 and EN 14491 for gas explosion venting

7.1 NFPA 68:2023 – Standard on explosion protection by deflagration venting

NFPA 68:2023 provides currently a more sophisticated vent sizing guidance for gas explosions than EN 14994:2007, which also includes the following

- Sizing for weak enclosures
- Sizing for geometries with turbulence inducing obstacles / obstructions
- Sizing for lean mixtures / partial volume approach

The sizing equations are rather complex and require iterative processes, hence hand calculations are time-consuming and prone to error.

Equations of NFPA 68 are divided in low strength calculations and high strength calculations.

Low strength calculations where $p_{red} \leq 0.5$ bar.

$$A_{v0} = \frac{A_s C}{\sqrt{p_{red}}} \quad [7.2.1a]$$

$$C = \frac{S_u \rho_u \lambda}{2 G_u C_d} \left[\left(\frac{P_{max} + 1}{P_0 + 1} \right)^{\frac{1}{\gamma_b}} - 1 \right] (P_0 + 1)^{\frac{1}{2}} \quad [7.2.1b]$$

where:

For applications involving gases with $P_{max} < 9$ barg and stoichiometric fuel concentration ≤ 10 %, equation [7.2.1.1] is permitted to be used in [7.2.1a].

7.2.1.1 is not used in VENT.iNG

$$C = 0.0223 \lambda S_u bar^{1/2} \quad [7.2.1.1]$$

High strength calculations where $pred > 0.5$ bar.

$$A_{V0} = A_s \frac{\left[1 - \left(\frac{pred + 1}{P_{max} + 1} \right)^{\frac{1}{y_b}} \right]}{\left[\frac{pred + 1}{P_{max} + 1} - \delta \right]} \frac{S_u \rho_u \lambda}{G_u C_d} \quad [7.2.2a]$$

$$\delta = \frac{\left[\left(\frac{P_{stat} + 1}{P_{max} + 1} \right)^{\frac{1}{y_b}} - 1 \right]}{\left[\frac{P_{max} + 1}{P_0 + 1} - 1 \right]} \quad [7.2.2b]$$

A certain safety distance is required between $pred$ and p_{stat} , which is given as follows. This is valid for both low and high strength calculation.

$$pred \leq 0.1 \text{ barg}, \quad p_{stat} \leq pred - 0.024 \text{ barg}$$

$$pred > 0.1 \text{ barg}, \quad p_{stat} < 0.75 * pred$$

Turbulent flame enhancement factor λ 7.2.6

Baseline value for λ_0 of λ shall be calculated by [7.2.6.1 a-f]

$$\varphi_1 = \begin{cases} 1, & \text{if } Re_f < 4000 \\ \left(\frac{Re_f}{4000} \right)^\theta, & \text{if } Re_f \geq 4000 \end{cases} \quad [7.2.6.1a]$$

$$Re_f = \frac{\rho_u S_u \left(\frac{D_h}{2} \right)}{\mu_u} \quad [7.2.6.1b]$$

$$\varphi_2 = \max \left\{ 1, \beta_1 \left(\frac{Re_v}{10^6} \right)^{\left(\frac{\beta_2}{S_u} \right)^{0.5}} \right\} \quad [7.2.6.1c]$$

$$Re_v = \frac{\rho_u u_v \left(\frac{D_v}{2} \right)}{\mu_u} \quad [7.2.6.1d]$$

$$u_v = \min \left\{ \sqrt{\frac{2 \times 10^5 * pred}{\rho_u}}, a_u \right\} \quad [7.2.6.1e]$$

$$\lambda_0 = \varphi_1 \varphi_2 \quad [7.2.6.1f]$$

Influence of surface area of obstacles 7.2.6.2

The following equipment and structures shall be included in the calculation of the surface of obstacles.

- "Piping, tubing, and conduit with diameters greater than 1/2 inch
- Structural columns, beams, and joists
- Stairways and railings
- Equipment with a characteristic dimension in the range of 2 inch. to 20 in. (5.1 cm to 51 cm)"

$$A_{obs} < 0.2A_s, \quad \lambda_1 = \lambda_0 \quad [7.2.6.3]$$

$$A_{obs} > 0.2A_s, \quad \lambda_1 = \lambda_0 \exp \sqrt{\frac{A_{obs}}{A_s} - 2} \quad [7.2.6.4]$$

Influence of elevated length / diameter ratio 7.2.6.7

$$\text{For } 2.5 \geq \frac{L}{D} \leq 5 \quad [7.2.6.7]$$

$$\lambda = \lambda_1 \left[1 + \left(\frac{\frac{L}{D}}{2.5} - 1 \right)^2 \right] \quad [7.2.6.7]$$

where:

$$Su < 3 \frac{m}{s}; P_{max} < 10 \text{ barg}; \text{Maximum air velocity} \leq \frac{5m}{s}; p_{red} \leq 2 \text{ barg}$$

$$\text{For } \frac{L}{D} \leq 2.5$$

$$\lambda = \lambda_1$$

Partial volume effects 7.3

A partial volume fill fraction, defined as X_r , shall be calculated as follows.

$$X_r = \left(\frac{\frac{V_{gas}}{V_{enc} - V_{solid}}}{X_{St}} \right) \quad [7.3.2]$$

$$\text{If } X_r < 1$$

$$A_{v1} = A_{v0} X_r^{\frac{1}{3}} \sqrt{\frac{X_r - \Pi}{1 - \Pi}} \quad [7.3.3]$$

$$\Pi = \text{Pred}/P_{\max}$$

$$\text{If } X_r \geq 1$$

$$A_{v1} = A_{v0}$$

Effects of panel inertia 7.4

$$M_T = \left[\frac{\text{pred}^{0.2} * n^{0.3} * V}{(S_u * \lambda)^{0.5}} \right]^{1.67} \quad [7.4.2]$$

$$\text{If } M > M_T$$

$$A_{v2} = A_{v1} * F_{SH} \left[1 + \frac{(0.05 * M^{0.6} * (S_u * \lambda)^{0.5})}{n^{0.3} * V * \text{pred}^{0.2}} \right] \quad [7.4.3]$$

$$V_{enc} \text{ must be } > 1 \text{ m}^3$$

$$\text{if } M < M_T, A_{v2} = A_{v1}$$

Effects of vent ducts 7.5

Vent ducts have an influence on the reduced explosion pressure due to secondary explosions in the duct. To evaluate the influence of the vent duct on the venting process, equations for ducts up to 3 m and between 3 and 6 m are provided. Different to previously described approaches to calculate the influence of vent ducts, the equations below result in lower pressures which need to be used in the overall equation, to determine a higher vent area.

For vent ducts < 3 m and shorter than four duct hydraulic diameter, equation 7.5.2.1 shall be permitted to determine p'_{red} .

$$p'_{red} = 0.779 * p_{red}^{1.161} \quad [7.5.2.1]$$

For vent duct ≥ 3 m, ≤ 6 m and shorter vent ducts longer than four duct hydraulic diameter, equation 7.5.2.1 shall be permitted to determine p'_{red} .

$$p'_{red} = 0.172 * p_{red}^{1.936} \quad [7.5.2.2]$$

For longer vent duct appropriate testing shall be done.

For vent ducts with lengths < than one hydraulic diameter no correction is required.

Where

A_{V0} = vent area calculated by [7.2.1a] in m^2

A_{V1} = vent area for partial volume calculation [7.3.3] in m^2

A_{V2} = vent area for panel inertia [7.4.3] in m^2

A_s = enclosure internal surface area in m^2 determined following [7.2.5]

C_d = vent flow discharge coefficient, determined according to [7.2.4] = 0.7 unless the vent occupies an entire wall of the enclosure in which case 0.8 shall be used

D_h = enclosure hydraulic diameter $\left[\frac{m}{s}\right]$

D_v = vent diameter determined through iterative calculation $\left[\frac{m}{s}\right]$

$F_{SH} = 1$ for translating panels or 1.1 for hinged panels

G_u = unburned gas – air mixture sonic flow mass flux in $\frac{kg}{m^2s} = 230.1 \frac{kg}{m^2s}$ for enclosure initially at ambient temperatures

M_T = threshold mass $\left[\frac{kg}{m^2}\right]$

n = number of panels

p_{stat} = static activation pressure of explosion venting device

P_{max} = maximum explosion pressure developed in a contained deflagration in barg

P_0 = enclosure pressure before ignition in barg

p_{red} = reduced explosion overpressure in bar

p'_{red} = lower corrected value for reduced explosion overpressure

for vent ducts to be used in iterative process in barg

S_u = fundamental burning velocity of gas – air mixture in m/s

u_v = maximum velocity through vent $\left[\frac{m}{s}\right]$

V_{gas} = maximum volume of gas that can be mixed with air in the enclosure

V_{enc} = enclosure volume

V_{solid} = volume of solid objects X_r = fill fraction

X_{St} = stoichiometric volume concentration of gas

$\beta_1 = 1.23$

$$\beta_2 = 2.37 * 10^{-3} \left[\frac{m}{s} \right]$$

$$\mu_u = \text{unburned gas air mixture dynamic viscosity} \left[\frac{kg}{m * s} \right]$$

$$\rho_u = \text{mass density of unburned gas - air mixture in } \frac{kg}{m^3} = 1.2 \frac{kg}{m^3} \text{ for gases with stoichiometric concentrations less than 5 vol \% and initially ambient temperatures}$$

$$\lambda = \text{ratio of gas - air mixture burning velocity accounting for turbulence and flame instabilities in vented deflagration to the fundamental (laminar) burning velocity, determined according to [7.2.6]}$$

$$y_b = \text{ratio of specific heats for burned gas - air mixture} = 1.15 \text{ for gases with stoichiometric concentrations less than 5 vol \% and initially ambient temperatures}$$

$$\theta = 0.39$$

$$\Pi = P_{red}/P_{max}$$

7.2 EN 14994:2007 – Gas explosion venting protective systems

The EN 14994:2007 is mainly designed to calculate explosion vent areas for simple geometries without many obstructions, which could cause turbulence and hence cause increased explosion overpressures.

The applicability of this standard for low reduced explosion overpressures and low activation pressures of the vent panels is limited to 0.1 barg, which is above the possibilities of NFPA 68:2023.

The standard is currently under revision and will likely include more sophisticated sizing methods for complex applications in the future.

The basic equations of the standard and its boundary conditions are described as follows

$$A = \left(\left((0.1265 * \lg(KG) - 0.0567) * pred^{-0.5817} \right) + \left(0.1754 * pred^{-0.5722} * (pstat - 0.1bar) \right) \right) * V^{\frac{1}{3}} \quad [1]$$

$$A_v = \frac{A}{E_f} \quad [2]$$

where:

A = geometrical vent area ($E_f = 1$), in m^2

A_v = vent area of an explosion venting device with efficiency ($E_f < 1$), in m^2

KG = gas explosion constant in $m * bar/s$

$pred$ = reduced explosion overpressure in bar

$pstat$ = static activation pressure of explosion venting device

E_f = venting efficiency of explosion venting device
= 1 for devices with an area specific mass of less than $0.5 \text{ kg}/m^2$

V = volume in m^3

Equation 1 and 2 is valid for:

$$KG \leq 550 \text{ m} * \text{bar}/s$$

$$0.1 \leq pstat \leq 0.5 \text{ bar}$$

$$pred \leq 2 \text{ bar}$$

$$pred > pstat + 0.05 \text{ bar}$$

$$V \leq 1000 \text{ m}^3$$

$$\frac{L}{D} \leq 2$$

Initial conditions: ambient

Effect of vent ducts

For vent ducts up to 3 m the influence of the vent duct on the reduced explosion pressure is described by

$$p'_{red} = 1.24 * pred^{0.8614} \quad [11]$$

For vent ducts above 3 m and up to 6 m, the influence of the vent duct on the reduced explosion pressure is described by

$$p'_{red} = 2.48 * pred^{0.5165} \quad [12]$$

with

p'_{red}: maximum reduced explosion overpressure with vent duct, in barg

pred: maximum reduced explosion overpressure without vent duct, in barg

Equation 11 and 12 are valid for:

$$Su \leq 2.86 \text{ m/s}$$

$$0.1 \leq p_{stat} \leq 0.5 \text{ bar}$$

$$pred \leq 2 \text{ bar}$$

$$V \leq 1000 \text{ m}^3$$

Initial conditions: ambient

7.3 Flame length calculations

Flame lengths of explosion venting of gas explosion can be calculated using the following equations.

EN 14994:2007	NFPA 68:2023
Flame length - Horizontal venting $L_F \approx 5 * V^{\frac{1}{3}}$ Flame length - Vertical venting <i>no equation available</i> with $L_F = \text{flame length (m)}$ $V = \text{enclosure volume (m}^3\text{)}$ for: $0.1 \text{ m}^3 < V < 50 \text{ m}^3$ $p_{\text{stat}} \leq 0.1 \text{ bar}$ $0.1 \text{ bar} < p_{\text{red,max}} \leq 1 \text{ bar}$ $P_{\text{max}} \leq 9 \text{ bar}$ $K_G \leq 100 \text{ bar*m/s}$ $L/D < 2$ Flame width – Horizontal and vertical venting <i>no equation available</i>	Flame length – horizontal and vertical venting $L_F \approx 3.1 * \left(\frac{V}{n}\right)^{0.402} \quad [7.6.1]$ $W_F = 0.5 * L_F$ with $L_F = \text{flame length (m)}$ $V = \text{enclosure volume (m}^3\text{)}$ $n = \text{number of evenly distributed vents}$ $W_F = \text{flame width measured radially from centerline of vent}$ for No limitations given in standard

7.4 Calculation of forces / external pressures

Maximum external pressures and forces can be calculated as follows

EN 14994:2007	NFPA 68:2023
Maximum external pressures $p_{ext,max} = \frac{1.24 * p_{red,max} * \left(\sqrt{\frac{A}{R}}\right)^{1.35}}{[1 + (\alpha/56)^2]}$ Where $p_{ext,max}$ = maximum external pressure (barg) R = distance to vent opening (m) α = direction towards the vent opening $\alpha = 0^\circ$ in front of the vent $\alpha = 90^\circ$ to the side of the vent for: $0.1 \text{ m}^3 < V \leq 250 \text{ m}^3$ $p_{stat} \leq 0.1 \text{ bar}$ $0.1 \text{ bar} < p_{red,max} \leq 1.0 \text{ bar}$ $P_{max} \leq 9 \text{ bar}$ $K_G \leq 100 \text{ bar*m/s}$ $L/D < 2$ Maximum pressure outside vent opening $0.2 \text{ bar} < p_{ext,max} \leq 1.0 \text{ bar}$ Recoil forces $F_{R,max} = 119 * A * p_{red,max}$ $\Delta t_R = 10^{-4} * K_G * V / (A * p_{red,max})$ $F_R = 0.52 * F_{R,max}$ $I_{R,max} = F_R * \Delta t_R$ Where $F_{R,max}$ = maximum recoil force (kN) Δt_R = duration of recoil force (s) F_R = static load due to recoil forces (kN) $I_{R,max}$ = Impuls transmitted by recoil force	No equations given in standard

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