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Design of silos for dust explosions: Determination of vent area sizes and explosion pressures

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ABSTRACT

The "Eurocode 1 – Actions on structures – Part 4: Silos and tanks" EN 1991-4 includes dust explosions as an accidental action for load combination in some design situations. Venting is the most widely used method to mitigate the effects of explosions. The area size of the venting devices installed in the silo will determine the development of internal overpressures in the event of an explosion, and thus the structural design of the silo. Also, the inertia and the activation pressure of the venting elements can influence the explosion pressures. The Eurocode 1 suggests using the German DIN-Report 140 to design the venting devices. However, other methods exist, such as the European standard EN 14491 and the American standard NFPA 68, which were not specifically developed for silos. In this study, the DIN-Report 140 has been analysed by calculating a wide range of cases, including different silo dimensions, materials (barley and wheat flour) and values of inertia and activation pressure of the venting devices. Three types of venting systems have been considered: bursting panels, explosion doors and light-weight concrete slabs. In addition, the DIN-Report 140 has been compared with current European and American venting standards. The results obtained in this study indicate that there are marked differences between the three methods considered, and that vent areas calculated according to DIN-Report 140 for either bursting panels or explosion doors seem to be very conservative. Uncertainties and limitations of DIN-Report 140 have been detected and discussed. The final goals of this study are to provide guidance on the determination of explosion loads and to contribute to the development of a single common practice for venting in silos.

1. Introduction

Silos are vertical containers used for storing granular or powdered materials. When designing the structure of any silo, determining the loads that are expected to act on it is a decisive starting point. Since the pioneering works by Roberts [1] and Janssen [2], extensive research into different aspects related to such structures has been carried out, including studies of wall pressures and flow patterns [3–5], eccentricities and unsymmetrical loads [6,7], wind pressures [8,9], and earthquake loads [10]. However, there are still many load cases and design problems that need to be addressed to achieve efficient and safe storage facilities for bulk solids [11,12].

Approved by the European Committee for Standardization in October 2005, the standard EN 1991-4:2006 "Eurocode 1 – Actions on structures – Part 4: Silos and tanks" [13] represented a significant advance in this field. EN 1991-4 covers many load conditions and could be considered as the most complete silo design code in use today [12]. Other codes and guidelines for design of silos exist; some of them are commonly used in different parts of the world, even outside their own country [12].

The Eurocode EN 1991-4 includes dust explosion loads as an accidental action for load combination in some specific design situations. Several compilations of major industrial accidents indicate that a significant number of dust explosions have occurred in silos [14]. Furthermore, an explosion can occur in auxiliary handling equipment, such as bucket elevators, conveyors, and dust collectors, and later spread throughout the system, producing devastating secondary explosions into the silo cells [15].

A dust explosion needs to be triggered by an ignition source of sufficient energy and also requires the simultaneous presence of dust clouds of appropriate concentration and an atmosphere containing enough oxygen to permit combustion [16]. The combustion process leads to a rapid and significant increase in pressure, typically up to 700–1000 kPa within a confined space; such pressures could lead to fracture and collapse of the silo or to a burst of the silo roof and upper walls with resultant flying projectiles [17]. Several types of potential ignition sources can be present in storage facilities [16], but dispersion of smouldering and flame nests generated by the self-heating of the material is one of the most

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common [18]. A wide range of materials that are stored in silos can cause dust explosions, including agricultural and food products [19], biomass materials [20], synthetic organic materials [21], and coal [22].

The European ATEX Directive 1999/92/EC [23] represented a milestone in both gas and dust explosion protection, raising the risk awareness and safety culture in many different process industries. This Directive, which is mandatory in the EU countries, establishes that employers must determine and assess the explosion risks and must take adequate measures against explosions. It therefore follows that a risk analysis should be applied to the storage facilities in order to identify the prevention and/or mitigation measures to be applied [24].

The Eurocode EN 1991-4 mentions three different methods to limit or avoid the potential damage: venting, suppression and containment [13]. The most widely used method in large vessels is venting, which consists in releasing combustion gases from the interior of the vessel through a device that opens at a predetermined pressure [16]. If vents are correctly sized, the flow discharge will maintain the explosion pressure below the value that the vessel is capable of resisting. However, venting neither prevents nor extinguishes an explosion; it merely reduces the explosion overpressure. Moreover, undesirable external effects, including flames, blast waves and flying debris, are to be expected [25].

The 2005 version of the Eurocode EN 1991-4 does not propose any calculation methodology for the mitigation measures mentioned above; it states that the accidental loads may be specified in the National Annex[1] or by the client for the individual project. However, EN 1991-4 includes an informative Annex H, entitled "Actions due to dust explosions", that explains how to decide the explosion loads in silos: where no venting is used, all structural elements should be designed for the maximum explosion pressure P_{max}, up to 700–1000 kPa as mentioned above; or where appropriate venting is used, a reduced explosion pressure P_{red} should be considered. The Annex H does not include any calculation method for P_{red}. Instead, it suggests following the DIN-Report 140 "Design of silos for dust explosions", which presents a set of nomograms based on large-scale explosion tests and numerical simulations [26,27].

In 2006 the European Committee for Standardization approved a standard on dust explosion venting, recently updated [28], which is based on the previous German guideline VDI 3673 [29]. This standard exploits the extensive European research on dust explosions carried out since the 60 s. Alternatively, the American standard NFPA 68 [30] is widely employed in different parts of the world. Both standards are primarily based on extensive experimental data.

The area of the venting device and the reduced explosion pressure are inversely related; the larger the vent area, the lower the pressure. Thus, the vent area size determines the explosion loads for structural design. Venting devices are installed in the roof or in the upper sidewall, but in some cases the roof area available for venting is insufficient or the proximity of other silos, equipment, or buildings turns venting unsafe; in other cases the roof and upper wall have a low strength, making the use of venting technically difficult and costly. It is known that venting standards sometimes calculate such large vent areas that they are difficult to implement in practice or are rejected due to their high cost [31,32].

Despite the inclusion of dust explosions in the Eurocode EN 1991-4, there seems to be a significant lack of awareness of this phenomenon and its effects. Unfortunately, the structural design and the explosion protection usually follow different paths, the latter being introduced in a final step of the project or even when the storage facility has already been erected, producing inconveniences and costly modifications in some cases.

The analysis of the application of empirical formulas and charts provided by guidelines and standards to different situations encountered in practice is necessary to detect discrepancies and potential aspects for improving. The objective of this study was to analyse the DIN-Report 140, which is the method suggested by the Eurocode EN 1991-4 for designing venting devices in silos. In addition, the results have been compared to current European and American venting standards. The ultimate aims of this research are to provide guidance to Eurocode users on the determination of explosion loads and to contribute to the development of a single common practice for the design of vent areas in silos.

2. Methods for determining vent area sizes

The DIN-Report 140 presents a series of nomograms to calculate vent area sizes and specifies that this method applies to different types of pressure-relief devices: inertia-free vent panels, known as bursting discs/panels; lids with inertia that lift without rotation up to a certain height; and flaps with inertia that rotate and must be arrested at a particular angle, usually known as hinged doors or explosion doors. One example of these nomograms was presented by Nasr et al. [27]. Table 1 shows the range of application of the nomograms.[2]

The nomograms permit to determine either the reduced pressure P_{red} for a known pressure-relief area A or the size of the vent area for a known reduced pressure. In both cases it is necessary to know the characteristic constant K_{St} [33]. The set of nomograms are classified into two groups, nomograms for lids and nomograms for flaps. Each group contains nomograms for different height/diameter ratios of the silo, from $H/D = 1$ to $H/D = 14$; the importance of the H/D ratio on explosion development is well known [34,35]. The DIN-Report 140 defines two parameters, K_{p} and K_{m}, which are included in the nomograms and permit to relate the reduced overpressure to the vent area (Eqs. (1) and (2)).

$$K_m = \frac{m^{1/2} \cdot K_{St}^{5/4} \cdot V^{1/24}}{n^{1/4}} \tag{1}$$

$$K_p = \frac{V^{5/6} \cdot K_{St}}{A} \tag{2}$$

where m is the mass of the venting element in relation to the pressure-relief area (kg/m^2), K_{St} is the characteristic constant (bar m/s), which is determined experimentally in laboratory [33], V is the volume of the silo (m^3), n is the number of venting elements, and A is the total vent area (m^2).

It is important to note that P_{max} and K_{St} should be presented in bar and bar·m s^{-1}, respectively, according to standards EN 14034-1 [36] and EN 14034-2 [33]. The three methods included in this study use pressures in bars. These considerations have been observed throughout the paper. However, the results are presented in SI units to facilitate the comparison with other types of loads (1 bar = 100 kPa).

The total activation pressure P_{a} of the relief device, defined by Eq. (3), is the sum of the pressure due to gravitational forces (m g) and the pressure due to any restraining forces ΔP_{a}; such restraining forces cease to act after the activation of the venting element.

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[1] The National Standards implement Eurocodes in each EU member and comprise the full text of the Eurocode, as published by CEN, which may be followed by a National Annex. The National Annex may contain information on those parameters which are left open in the Eurocode for national choice to be used for the design of structures to be constructed in the country concerned.

[2] Although the two methods included in Table 1 use a different nomenclature, this has been standardised here for clarity.