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Research Paper

Dust explosions in an experimental test silo: Influence of length/diameter ratio on vent area sizes

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Vented dust explosion tests have been conducted in an experimental test silo in order to analyse the effect of the length/diameter ratio (L/D). The modular design of the silo permitted the assembling of four different vessels with different geometries. The tests were carried out with wheat flour and maize starch, using three different vent area sizes. The silo was equipped with instrumentation which recorded the pressure generated by the explosion at various points in the silo, as well as the instant when the vent panel opened. The length/diameter ratio has been included in the empirical correlations currently employed in standards EN 14491 and NFPA 68 for calculating the size of vents. However, there are marked differences between the two standards when applied to certain situations, in part due to a different vent area correction for slenderness. The results obtained in this experimental test programme were compared with the standards, and indicated the advisability of applying an increase in vent area in elongated vessels when L/D > 1, as stated in EN 14491. However, this same standard appears to apply an excessively severe correction in some situations.

1. Introduction

Experimental tests have been carried out in silos over more than a century (Couto, Ruiz, Herráez, Moran, & Aguado, 2013; Janssen, 1895; Larsson, Lestander, Crompton, Melin, & Sokhansanj, 2012; Munch-Andersen & Nielsen, 1986; Negi, Lu, & Jofriet, 1997; Ooi, Chen, & Rotter, 1998; Ramírez, Nielsen, & Ayuga, 2010; Roberts, 1883; Sielamowicz, Czech, & Kowalewski, 2011). However, there are still many questions that need to be addressed in order to achieve efficient and safe designs for the silos that are used in agriculture and the process industries (Ayuga, 2008; Barletta et al., 2015; Bradley, Pittman, Bingley, Farnish, & Pickering, 2000).

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Nomenclature

A_0	vent area for a compact vessel (i.e. vent area without adding the L/D correction), m^2
A_1	total vent area required, m^2
$A_{o\text{-}EN}$	vent area according to EN 14491without adding the L/D correction, m^2
$A_{o\text{-}NFPA}$	vent area according to NFPA 68 without adding the L/D correction, m^2
$A_{1\text{-}EN}$	total vent area according to EN 14491, m^2
$A_{1\text{-}NFPA}$	total vent area according to NFPA 68, m^2
A_{exp}	vent area used in the experimental test, m^2
K_{St}	characteristic constant of the dust, bar m s^{-1}
L/D	length-to-diameter ratio of the vessel to be protected (equal to the height-to-diameter ratio of the silo), m m^{-1}
P_{act}	activation pressure of the venting device measured in the explosion test, bar
P_{max}	maximum explosion pressure of the dust, bar
P_{red}	maximum pressure generated by a vented explosion, bar
P_{stat}	static activation pressure of the venting device, bar
V	volume of the silo to be protected, m^3
ΔA	increase in vent area size due to vessel slenderness, or L/D correction, m^2
α	area increase ratio or unit correction of the area due to vessel slenderness, m^2

Dust explosions represent a significant threat and can occur if fine dust particles are dispersed in the air as a cloud in the presence of an ignition source (Eckhoff, 2003). Many serious accidents have been reported (Abbasi & Abbasi, 2007), and statistics indicate that the number of incidents per year is still significant and may even be increasing (Blair, 2007; Yan & Yu, 2012). This is due to the improper handling and storage of materials and suggests a lack of risk awareness and safety culture in relation to flammable dusts. A dust explosion requires the simultaneous presence of a dust cloud of appropriate concentration and a suitable ignition source of sufficient energy. Such a situation can trigger a violent combustion reaction, with flame propagation through the entire burnable dust/air mixture and the production of large quantities of heat and reaction products. When this occurs within a confined space there is a rapid and significant increase in pressure, typically up to 7–10 bar (700–1000 kPa).

A very wide range of materials can cause dust explosions, including agricultural and food industry products and various biomass materials (Huéscar Medina et al., 2015; Ramírez, García-Torrent, & Aguado, 2009). In some cases, the main product itself is sufficiently fine to generate explosive dust clouds if dispersed in air, such as with wheat flour or maize starch. In other cases, the main product is quite coarse, such as grain and wood pellets, and the fine dust constitutes only a small, but undesired mass fraction of the total bulk material, generated by the abrasion and crushing of the larger material particles during the product handling processes (Eckhoff, 2009).

Several types of potential ignition sources can trigger a dust explosion in plants that handle, store or process bulk solids. Ignition of dust layers and deposits accumulated on hot surfaces and overheated equipment is a frequent cause of fires and explosions (Lebecki, Dyduch, Fibich, & Śliż, 2003). Dispersion of either smouldering or flame nests generated by the self-heating of the material is another possibility (Ramírez, García-Torrent, & Tascón, 2010). Other likely ignition sources are electrical and mechanical sparks, welding and cutting operations, static electricity, and flames from earlier fires or explosions (Abbasi & Abbasi, 2007).

When the risk of explosion is not adequately addressed, the consequences can be catastrophic. In 2008, a series of dust explosions occurred at a cane sugar manufacturing facility in Georgia, USA, killing 14 workers and injuring 36 others (Vorderbrueggen, 2011). The investigation revealed that the first dust explosion occurred in an enclosed steel belt conveyor located below the sugar silos but the ignition source remained unknown. The subsequent explosions and fires destroyed the sugar packing buildings, palletiser room, and silos, and severely damaged other areas. Another illustrative example is the severe dust explosion that occurred in a grain storage complex at Blaye (France), in 1997, killing 11 people. The investigation concluded that the most likely sources of ignition were either a malfunction of the fan on the centralised dust collecting system or self-ignition caused by a self-heating process of the dust collected coupled with a high ambient temperature (Masson, 1998). Many other dust explosions have been reported in recent years, involving different types of industrial facilities and equipment, such as dust collecting systems (Yuan, Khakzad, Khan, & Amyotte, 2015), dryers (Febo, 2015; Telmo Miranda, Muñoz Camacho, Fraguela Formoso, & Rodríguez García, 2013), flour mills (Marmo & Demichela, 2012), grain silos (Ogle, Dillon, & Fecke, 2014; Spósito & Solis, 2013) and sugar silos (Westran, Sykes, Hawksworth, & Eaton, 2008). A complete compilation of major historical accidents and statistics can be found elsewhere (Abbasi & Abbasi, 2007; Blair, 2007; Eckhoff, 2003; Yan & Yu, 2012; Yuan et al., 2015). In addition, data about accidents in biomass and biofuels facilities have recently been collected and seem to indicate that more explosions are occurring (Calvo Olivares, Rivera, & Núnez McLeod, 2014; Casson Moreno & Cozzani, 2015).

According to several reports, a significant number of severe dust explosions have occurred in silos (Abbasi & Abbasi, 2007; Eckhoff, 2003). Bulk products form potentially explosive dust clouds inside a silo during filling and emptying. Moreover, a primary explosion can occurred outside the silo, in conveyors, bucket elevators, dust collectors, etc., and later spread with increasing violence throughout the system, producing devastating secondary explosions (Taveau, 2011). Hauert, Vogl, and Radant (1996) carried out a comprehensive experimental programme to determine the characteristics of dust clouds in a 12 m^3 silo and the subsequent dust explosion pressures. In addition, computational fluid dynamics (CFD) simulations have been used to analyse the dust distribution in this 12 m^3 silo during pneumatic axial filling (Rani, Aziz, & Gimbun, 2015), and the results showed that the dust concentration in all regions of the silo exceed the lower explosion limit (LEL), i.e. the minimum explosive concentration (CEN,