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Analysis of dust distribution in silo during axial filling using computational fluid dynamics: Assessment on dust explosion likelihood

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ABSTRACT

In this study, the dust distribution in a silo during axial filling was modelled using a commercial computational fluid dynamics (CFD) code. The work focused on the dust concentration distribution in the silo, for evaluating the likelihood of a dust explosion in the silo. The simulation was conducted using a combination of renormalized (RNG) k-epsilon and discrete phase models, with standard pressure interpolation and a second order upwind scheme. The predicted dust concentration distribution showed a good agreement with experimental data adopted from the literature. It was found that the dust concentration distribution was influenced by mean velocity and turbulence flow. The simulation results suggest that the cornstarch concentration inside the silo was always above the lower explosion limit (LEL), hence requiring a mitigating action or a control system to reduce the explosion risk.

1. Introduction

A silo is often used in the industry as a vessel for storing bulk materials, i.e. agricultural, carbonaceous, chemical and plastic powder with volumes ranging from a few cubic meters to a few thousand cubic meters. To store the bulk material, the silo is filled using a cyclone, pneumatic transport pipe or bucket elevator. The filling process will generate an initial turbulence, which will induce the dispersion of dust particles in the air. The flammable dust cloud may pose a significant risk to industries that use, handle and produce bulk powders. Moreover, it may trigger a secondary explosion, which can cause fatality, injuries and massive material damage. This implies that the majority of industrial plants with dust processing equipment are vulnerable to dust explosions. Due to the large masses, the devastating consequence from fire and explosion in silos is substantial. It would be more severe when the silos are interconnected either directly or via the solids handling equipment enabling the explosion to propagate from one silo to another. For instance, in 1997, a grain dust fire and explosion occurred in Blaye, France, which caused 11 fatalities and one injury. The explosion also demolished a vertical grain storage silo and other process equipment (Masson, 1998).

Due to the devastating consequences of a dust explosion, many studies have been performed to understand the risk as well as to develop the prevention and mitigation approach. Many earlier works pay greater attention to the ignition sensitivity, explosion severity and venting. For instance, Eckhoff and Fuhre (1984) proposed a correlation for the vent area for a dust explosion in a 500 m^3 silo. The effect of dust concentration and ignition location on flame propagation and pressure

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expansion in a 236 m^3 silo was investigated by Eckhoff et al. (1987). Their work shows that the dust distribution is significantly affected by injection configuration. They concluded that the explosion severity was notably increased when the dust concentration falls within the worst-case region (a region with dust concentrations between LEL and UEL) and the ignition location is far away from the vent at the top of the silo. Hauert et al. (1996) measured the dust concentration, turbulence parameters and reduced explosion pressure in a 9.4 m^3 silo. They found that tangential filling may reduce explosion risk and severity compared to axial filling. Zhong and Deng (2000) simulated a cornstarch explosion in a 12 m^3 silo using a coupled species transport and Eulerian–Lagrangian model and found that turbulence induced by the flame front had a great influence on the explosion violence compared to the initial turbulence. Van Wingerden et al. (2001) demonstrated that computational fluid dynamics (CFD) can be used as a tool to predict the consequences of a dust explosion in various industrial equipments. Simulation of a cornstarch explosion in a vented silo was carried out by Zhong et al. (2001). They treated the particle phase as a continuous phase and solved the combustion process by employing an one-step non-inverse Arrhenius expression in conjunction with an Eddy Break-up model. Skjold et al. (2005) used a dust explosion simulation code (DESC) to simulate axial and root mean square (RMS) velocities, dust concentration, maximum reduced explosion pressure and flame development in a 9.4 m^3 silo, similar to those experimentally studied by Hauert et al. (1996). Their result suggests that the size of the venting area and ignition location affected the explosion pressure significantly. Skjold et al. (2006) demonstrated the application of the software DESC to simulate a dust explosion in complex industrial equipment. Tascón et al. (2011) performed a numerical analysis using DESC on the influence of the venting size on pressure development in a vented 12 m^3 silo. They reported a good agreement on the pressure development compared to the NFPA 68 standard. Ramírez et al. (2010) studied the thermal stability of various agricultural materials stored in a silo. All tested materials showed the ability to undergo self-ignition and self-heating when stored in a silo under certain conditions. Bind et al. (2012) used the CFD code FLUENT to simulate a dust explosion in a 10.3 m^3 silo. They demonstrated that combining of particle-scale combustion processes with cloud-scale transport processes was useful for modelling dust explosions. In recent years, CFD simulation was employed to perform a risk assessments associated with probabilistic analysis for biomass dust explosions in bulk storage as attempted by Coffey and Price (2012). In another study, Silva et al. (2012) examined the influence of methane gas on a cornstarch dust explosion in a 1 m^3 silo using the CFD code CFX. They found that the presence of methane reduced the minimum ignition temperature of the cornstarch powder in the storage unit. Recently, Tascón and Aguado (2015) reported on the likelihood of a severe dust explosion when the point of ignition was located far away from the vent combined with a higher dust concentration. Despite previous studies, little is known about the local dust explosion likelihood inside the silo during the filling process. It is understood that the explosion risk and severity is affected by the dust concentration. Hence, this work focuses on the numerical study of dust cloud generation, dust concentration distribution and possibilities of dust explosion occurrence by comparing to the determined concentration to the LEL value in the specific region in a silo.

The knowledge of the gas–solid concentration and dispersion during the filling operation is vital for dust explosion hazard assessment. In practice, the turbulent flow responsible for the dust cloud formation due to a silo being filled is not analogous to natural conditions. Since ignition sensitivity and explosion severity are affected by the dust cloud, it is necessary to identify the dust concentration level and explosive range in air. The experiments by Hauert and Vogl (1995) represent an important initial contribution toward understanding multiphase flow in a silo. Recently, Klippel et al. (2014) investigated the dust concentration during the filling process of a 50 m^3 silo with various filling injection points and reported that the dust concentration is above the LEL value, where more explosive dust cloud generated from homogeneous filling compared to axial pneumatic filling. Several researchers also studied dust cloud formation processes in various geometries. Several authors (i.e. Kosinski et al., 2005; Kosinski and Hoffmann, 2005; Kosinski, 2011) studied the formation and behaviour of a flammable dust cloud in air behind shock waves in a rectangular channel. Meanwhile, Kosinski and Hoffmann (2007) studied the effect of particle–particle and particle–wall collisions for dense particle clouds in a channel. Turbulent dust clouds in a cylindrical chamber were studied by Gupta and Kumar (2007), and Radandt et al. (2009) studied dust cloud characteristics in a conveying system. Murillo et al. (2013) studied the characteristics of gas–solid flow inside a modified Hartmann tube.

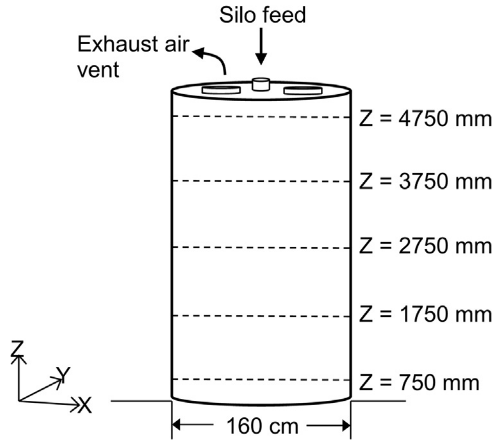

Fig. 1 – Cylindrical silo geometry with various axial positions.

CFD was chosen for this work because it is relatively low cost compared to experimental work. Moreover, CFD is capable to simulate real conditions with specific phenomena and has the ability to produce comprehensive information of the process. Furthermore, CFD allows safety studies to be performed without exposure to the actual safety risk. This work extends the results from our previous work (Rani et al., 2014a,b) which is limited to the mean and RMS velocities in a silo during an axial filling process into analysis on the dust explosion likelihood from the dust concentration distribution point of view.

2. Computational approach

2.1. *Description of the silo*

A gas–solid flow in a cylindrical silo with a diameter of 1.6 m and height of 5 m, which was experimentally studied by Hauert and Vogl (1995), was considered in this work (Fig. 1). The initial conditions are shown in Table 1. Hauert and Vogl (1995) studied a silo with a height of 5.6 m including the bin-hopper at the bottom. However, their measurement and analysis only concerned the cylindrical section of the silo. Furthermore, a subsequent study by Hauert et al. (1996) also used a similar silo configuration, but the bin-hopper was not considered since it was filled with sand. Thus, the bottom part of the silo is effectively a flat surface. Therefore, a flat-bottomed geometry was considered in this work for the sake of consistency with the case studied by Hauert and Vogl (1995).

2.2. *Turbulence modelling*

Turbulence models play an important role in predicting both gas and particle flows accurately. In this work, based on

Table 1 – Initial parameters for cornstarch-air simulation.

Particle mean diameter	15 μm
Feeding rate	0.429 kg/s
Silo feed surface diameter	0.075 m
Conveying velocity	23 m/s
Temperature	300 K

Hauert and Vogl (1995).