Numerical Simulation Study on the Venting Characteristics of Dust Collectors Under Dust Explosion Loading

Chang Li, Kun Shu*
School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China
**Corresponding Author.*

Abstract: Dust explosion accidents in dust collectors occur frequently in industrial production. Explosion venting is a critical technical measure to mitigate overpressure within dust collectors. Based on the explosion characteristics of coking coal dust, this study employs the DESC simulation tool to numerically investigate the venting dynamics in coking coal dust collectors. The results indicate that as the coking coal dust concentration increases, both the explosion overpressure and flame propagation speed inside the dust collector initially rise and then decline, peaking at 1000 g/m^3. Without venting measures, the explosion overpressure in the dust collector is significantly higher than in vented scenarios. The maximum explosion pressure inside the dust collector decreases with an increase in venting area, whereas the maximum explosion overpressure increases as the venting activation pressure decreases.

Keywords: Dust Collector; Coking Coal Dust; Numerical Simulation; Dust Explosion; Flame Cloud

1. Introduction

With the continuous advancement of production technologies, many industries involving explosive dust have significantly improved production efficiency [1-2]. However, this has also led to a substantial increase in dust generation during production processes, resulting in frequent dust explosion accidents within dust collectors. For instance, on February 18, 2015, an explosion occurred in a dust collector at the ExxonMobil Torrance Refinery in the United States [3]. In this incident, the dust collector was severely damaged by the explosion, leaving four employees injured. On April 29, 2016, an aluminum dust explosion accident took place at a hardware processing plant in Guangdong Province [4]. The accident was triggered by an initial aluminum dust explosion in the dust collection duct, which subsequently caused a secondary explosion within the workshop, ultimately resulting in 4 fatalities and 6 injuries. Dust collectors generally consist of internal structures and pipeline systems [5-6]. An explosion occurring within the internal structure can propagate flames through external pipelines, thereby posing hazards to personnel or equipment operating near the ducting.

In the field of dust explosion research, Skjold et al. [7-12] refined the dust explosion calculations in the DESC module of the FLACS software, validating its reliability in simulating corn starch and coal dust explosions. Nicholas et al. [13] investigated the scenario where an explosion propagates through a connecting pipeline between two vessels after the initial explosion in one vessel using FLACS numerical simulation. The simulation results revealed the maximum explosion overpressure (Pmax) in both vessels, based on which the venting areas for the two vessels under such conditions were designed. Alberto et al. [14] investigated the influence of the length-to-diameter ratio (L/D) of venting ducts on the internal explosion pressure. When L/D > 1, the peak explosion overpressure (P_{max}) of corn starch and wheat flour, along with the corresponding venting area (S), showed close agreement with the predicted values proposed in EN14491.Guo et al. [15] demonstrated that even low concentrations of coal dust can lead to an increase in chamber explosion pressure (P) and enhance flame propagation velocity (v) within the pipeline. The most pronounced effect was observed at a gas concentration of 9%. Given these findings, this study focuses on investigating the venting behavior of coke dust in dust collectors, aiming to provide a theoretical foundation for the optimized design of explosion venting systems.

2. Numerical Simulation

Using the coke coal dust from a pulse-jet bag filter in a coking plant [16] as the experimental medium, the 20L spherical explosion vessel was employed to obtain key explosion characteristics data, including the maximum explosion pressure (6.3 barg), minimum ignition energy of dust cloud, minimum ignition temperature, and lowest combustion temperature. These data were subsequently used to generate the Fuel file required for DESC [17] tool in FLCAS simulations. Based on the actual dimensions of the pulse-jet bag filter, a computational physical model was constructed using the DESC tool (as shown in Figure 1). The FLCAS software [18] was then utilized to simulate and analyze the venting behaviors (including explosion overpressure and flame propagation) under various conditions such as dust concentration, venting area, and venting activation pressure inside the filter.

The specific geometry of the dust collector consists of a lower frustum portion [19] with a 4 m × 4 m square base, a 16 m × 16 m square top surface, and a height of 6 m. The upper section is a rectangular cuboid measuring 16 m × 16 m × 14 m. Since FLCAS requires orthogonal grid settings, the inclined walls of the conical lower section would result in low wall grid porosity during meshing, potentially causing flame leakage that could affect dust explosion simulation results. To address this, the conical section was equally divided and converted into progressively shrinking cubes, forming a stepped inclined wall [20]. For FLCAS simulations, the collector interior was filled with uniformly distributed dust cloud (coke coal dust with 45 μ m particle size) under normal temperature and pressure conditions. The ignition source (10 kJ energy) was positioned at the geometric center of the dust collector.

All printed material, including text, illustrations, and charts, must be kept within the parameters. Please do not write or print outside of the column parameters. Margins are 2.5cm on the left side, 2.5cm on the right, 3.0cm on the top, and 2.5cm on the bottom. Paper orientation in all pages should be in portrait style.

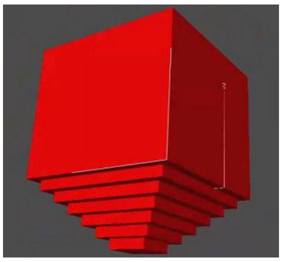


Figure 1. Physical Model of Dust Collector

3. Results and Analysis

3.1 Effect of Dust Concentration on Venting Process in Dust Collectors

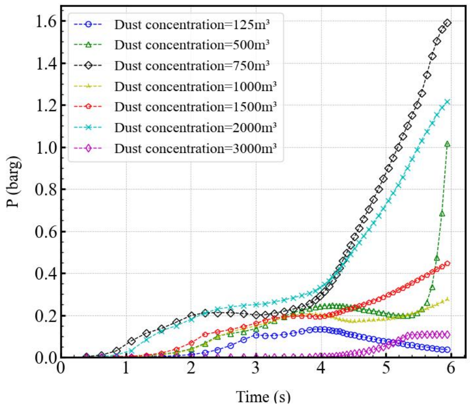


Figure 2. Pressure Variation Curves of Explosion under Different Dust Concentrations

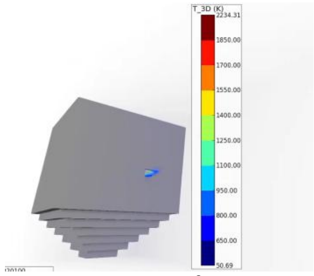
Dust concentration is a critical parameter affecting the consequences of dust explosions.

The variation law of explosion overpressure of coking coal dust in the dust collector with the concentration of dust mass is shown in Figure 2and Table 1The flame propagation processes at different dust concentrations are illustrated in Figure 3.

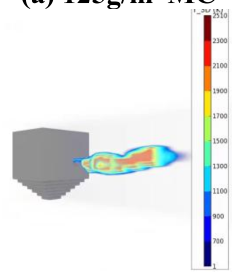
The results indicate that after ignition inside the dust collector, the explosion flame propagated from the upper section downward and eventually vented through the explosion relief opening. The maximum explosion overpressure initially increased and then decreased with rising coal dust concentration, peaking at 8.05 barg under a concentration of 1000 g/m³. This trend occurs because at lower concentrations, increasing dust mass enhances combustion intensity by providing more reactive particles. However, beyond a critical concentration (saturation point), limited oxygen availability prevents complete combustion of the excess dust. The unreacted particles absorb heat generated by the explosion, thereby suppressing the overpressure.

Table 1. Maximum Explosion Pressure at Different Dust Concentration

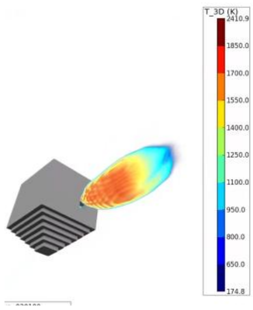
Dust mass concentration(g/m^3)	125	500	750	1000	1500	2000	3000
Maximum explosion pressure(barg)	0.133	0.174	0.105	0.790	0.960	1.240	0.500



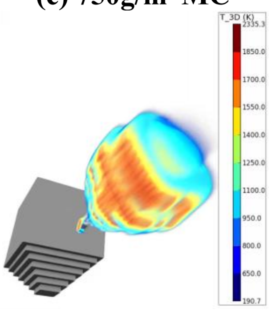
(a) 125g/m³ MC



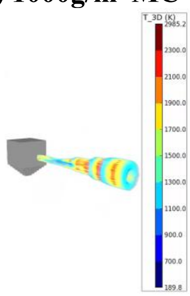
(b) 500g/m³ MC



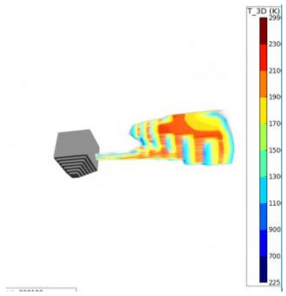
(c) 750g/m³ MC



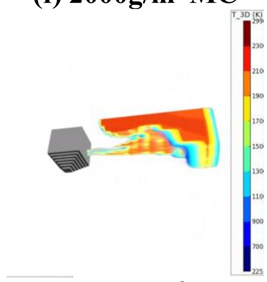
(d) 1000g/m³ MC



(e) 1500g/m³ MC



(f) 2000g/m³ MC



(g) 3000g/m³ MC

Figure 3. Flame Cloud Propagation Temperature in the Dust Collector at Different Dust Concentrations

3.2 The Influence of Venting Area on Explosion Consequences

Under the conditions of a single vent opening, a vent activation pressure of 0.1 barg, and a dust concentration of 2000 g/m³, the required vent area for a dust collector measuring 6 m × 16 m × 14 m was determined to be 64 m² according to the Guidelines for Dust Explosion Venting (GB/T 15605-2008). To investigate the overpressure characteristics under both substandard and compliant vent areas, the vent area was systematically varied from 4 m² to 64 m². As shown in Figure 4, when the vent area was only 4 m², the coking coal dust explosion reached the vent activation pressure (0.1 barg) at 3.1 s. Due to the significantly undersized vent area, the explosion overpressure continued to rise even after vent activation. However, as the vent area increased, both the time to reach activation pressure and the maximum vented pressure decreased. For example, when the vent area was increased to 16 m², the activation time was delayed to 0.63 s, and the maximum vented pressure was reduced to 0.48 barg. When the vent area met the standard requirement (64 m²), the maximum pressure inside the dust collector stabilized at 0.1 barg (equal to the vent activation pressure). This trend indicates that with a sufficiently large vent area, the pressure release rate through the vent opening far exceeds the pressure generation rate from the ongoing dust combustion. The vent area calculated using the Guidelines for Dust Explosion Venting (GB/T 15605-2008) effectively mitigates explosion overpressure in dust collectors.

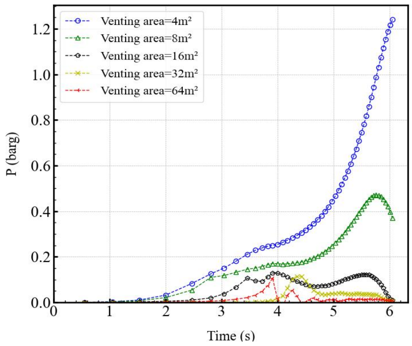


Figure 4. Overpressure-Time Curves Corresponding to Different Venting Areas

3.3 The Influence of Activation Pressure on Explosion Consequences

This section presents a simulation study on the consequences of coking coal dust explosions in a dust collector under different vent activation pressures. The study was conducted with vent activation pressures set at 0.1 bar, 0.2 bar, 0.3 bar, and 0.4 bar, respectively, under the following conditions: single vent opening, vent area of 4 m², and dust concentration of 2000 g/m³. Figure 5 illustrates the effect of vent activation pressure on explosion overpressure inside the dust collector. When the vent activation pressure was set at 0.4 bar, the maximum vented pressure in the dust collector was significantly higher than in other cases. This is attributed to the higher vent activation pressure, which prolongs the response time of the venting process, potentially leading to excessive internal pressure buildup. In contrast, when the vent activation pressure was lower, the venting process occurred more rapidly. The swift release of pressure and combustion gases effectively mitigated hazardous internal pressures, preventing further explosion escalation. These findings highlight that appropriately designing the vent activation pressure of dust collectors is crucial for effectively controlling equipment overpressure during explosions.

3.4 Effect of Initial Pressure on Explosion Consequences in Dust Collectors

Under conditions of 2000 g/m³ dust concentration, this study investigated the impact of initial pressures (1, 2, and 3 atmospheres) on explosion overpressure within the dust collector. As shown in Figure 6, when the initial pressure was 3 atm, the maximum vented pressure in the dust collector was significantly higher than under the other two conditions. The maximum vented pressure progressively decreased with reduction in initial pressure. The observed phenomenon can be attributed to the influence of initial pressure on gas dynamics:

(1) Higher initial pressures (3 atm) enhance gas expansion velocity and alter flow characteristics during venting, resulting in more vigorous post-vent gas flow.

(2) This accelerated discharge process leads to faster pressure transients, ultimately generating greater maximum vented pressures.

(3) Conversely, lower initial pressures (1 atm) exhibit moderated gas expansion behavior, yielding reduced overpressure magnitudes.

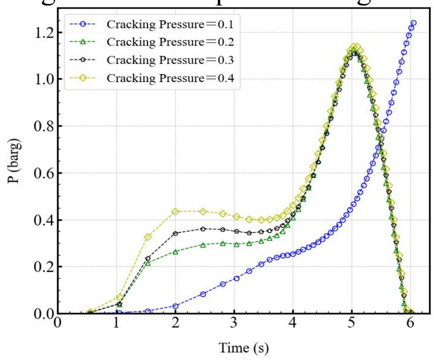


Figure 5. Overpressure-Time Curves under Different Activation Pressures

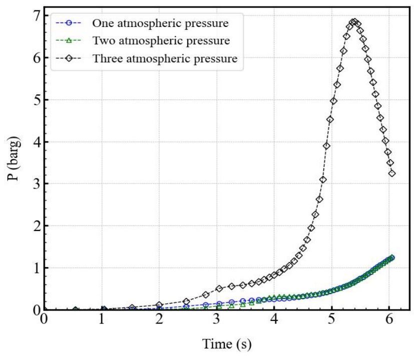


Figure 6. Overpressure-Time Curves under Different Initial Pressures

3.5 The Influence of Venting Ducts on Explosion Consequences

Venting ducts play a critical role in explosion venting for dust collectors, primarily serving to protect both the collector itself and connected equipment from explosion-induced shock and damage. This section examines the effects of vent duct presence and configuration on explosion venting performance through numerical simulations conducted under controlled conditions: a vent area of 4 m², vent activation pressure of 0.1 bar(g), and dust concentration of 2000 g/m³. As evidenced in Figure 7, the study reveals significant performance variations based on duct configuration. The most effective scenario occurs when a bent vent duct is installed on the sidewall of the dust collector, demonstrating both the lowest peak venting overpressure and minimal flame temperatures. In contrast, implementation of a short, straight vent duct shows negligible improvement over the non-ducted baseline condition, with nearly identical peak overpressure measurements. These findings underscore the importance of proper duct geometry in explosion protection systems, where bent configurations provide superior mitigation through enhanced flame disruption and pressure dissipation compared to straight duct alternatives.

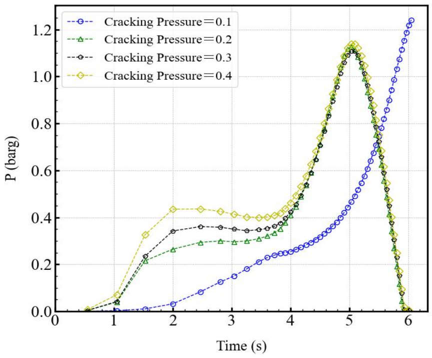


Figure 7. Overpressure-Time Curves under Different Venting Duct Conditions

4. Conclusion

As the dust concentration increases, both the maximum explosion pressure and flame propagation velocity of coke dust explosions inside the dust collector first increase and then decrease, peaking at 1000 g/m³.

The maximum venting pressure inside the dust collector decreases with an increase in venting area but increases with a decrease in venting activation pressure.

The activation pressure inside the dust collector affects the venting duration—the lower the activation pressure, the shorter the venting process, thereby more effectively mitigating equipment overpressure during an explosion.

When the initial pressure inside the dust collector is higher, the gas flow after venting becomes more intense, accelerating the venting process and ultimately leading to a higher maximum venting pressure.

When the dust collector has a curved venting duct on the side of its enclosure, both the maximum venting pressure and the peak flame temperature reach their lowest values.

In practical applications of dust collectors, it is essential to carefully consider the effects of activation pressure and internal initial pressure. Setting appropriate pressure levels contributes to the efficient and long-term operation of the dust collector.

References

[1] Deng X., Wang S., Yuan Z., & Li G. (2021). Numerical simulation of dust explosion venting in industrial filters: Effects of vent size and dust concentration. Journal of Loss Prevention in the Process Industries, 72, 104567.

[2] Cao W., Li J., & Zhang Y. (2019). CFD analysis of explosion venting dynamics in baghouse dust collectors under methane-coal dust hybrid mixtures. Powder Technology, 356, 451-463.

[3] Skjold T., Arntzen B. J., Hansen O. R., et al. (2015). Simulation of dust explosions in complex geometries with experimental validation. Journal of Hazardous Materials, 299, 155-163.

[4] Ning B, Zhang S, et al. Study on the influence of inlet duct on the performance of bag filters. Journal of Safety and Environment, 2013, 13(6): 58-63.

[5] Zheng M, Xuan S Y. Modification of dust collectors and pipeline optimization. Gold, 2010, 31(8): 32-34.

[6] Wang M. Electrostatic precipitator explosion at ExxonMobil Torrance Refinery. Modern Occupational Safety, 2017, (06): 86-90.

[7] Skjold T, Arntzen B J, Hansen O R, et al. Simulating dust explosions with the first version of DESC. Process Safety and Environmental Protection, 2005, 83(2): 151-160.

[8] Skjold T, Arntzen B J, Hansen O R, et al. Simulation of dust explosions in complex geometries with experimental input from standardized tests. Journal of Loss Prevention in the Process Industries, 2006, 19(2-3): 210-217.

[9] Skjold T. Review of the DESC project. Journal of Loss Prevention in the Process Industries, 2007, 20(4-6): 291-302.

[10]Skjold T, Castellanos D, Olsen K L, et al. Experimental and numerical investigations of constant volume dust and gas explosions in a 3.6 metre flame acceleration tube. Ninth International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions (ISHPMIE). 2012: 22-27.

[11]Skjold T. Flame propagation in dust clouds. Numerical simulation and experimental investigation. 2014, 425-446.

[12]Skjold T, Castellanos D, Olsen K L, et al. Experimental and numerical investigation of constant volume dust and gas explosions in a 3.6-m flame acceleration tube. Journal of Loss Prevention in the Process Industries, 2014, 30: 164-176.

[13]Nicholas R S, Mark BS. Consequence prediction for dust explosions involving interconnected vessels using computational fluid dynamics modeling. Journal of loss prevention in the process industries. 2020. 65: 104149.

[14]Tascon A A P J. Dust explosions in an experimental test silo: Influence of length/diameter ratio on vent area sizes. Biosystems Engineering, 2016, 148: 18-23.

[15]Guo C, Shao H, Jiang S, et al. Effect of low-concentration coal dust on gas explosion propagation law. Powder Technology, 2020, 367: 243-252.

[16]Xie X M, Zhang L L. Study on high-temperature combustion characteristics of coke coal with different particle sizes. Safety in Coal Mines, 2024, 55(08): 80-87.

[17]Yuan, C., & Khakzad, N. (2020). Computational fluid dynamics (CFD) modeling of dust explosion suppression in enclosed systems. Process Safety and Environmental Protection, 143, 164-175.

[18]Tascón A, Aguado P J. Simulations of vented dust explosions in a 5 m3 vessel. Powder Technology, 2017, 321: 409-418.

[19]Wu Y M, Ding J X, Wang X H, et al. Numerical simulation of tobacco dust explosions in silos. Industrial Safety and Environmental Protection, 2019, 45(05): 31-35.

[20]Kosinski, P., Hoffmann, A. C., & van Wachem, B. G. (2013). Numerical simulation of a dust explosion in a vented silo. Journal of Hazardous Materials, 256-257, 62-71.

