Examining the effect of reactivity parameters $S_{\mathrm{T},R}$ and χ on dust explosion venting

C. Regis L. Bauwens, Sergey B. Dorofeev
FM, Research Division
Norwood, Massachusetts, USA

1 Introduction

Dust explosions are a common hazard in industrial facilities handling combustible dusts, potentially resulting in significant loss of life and catastrophic damage to buildings and equipment. Despite their severity, the effective implementation of protection measures such as explosion venting, suppression, and isolation can largely mitigate these incidents. The proper application of these measures, however, must consider the inherent reactivity of the dust, which can vary significantly between different dusts [1, 2].

Characterizing dust reactivity poses a significant challenge, as the severity of a dust explosion depends on both the level of initial turbulence [3, 4] and the specific properties of the dust, such as particle size distribution [5]. Due to the lack of fundamental dust reactivity data, standardized empirical tests have been developed to measure the reactivity of specific dust samples. In these tests, dust reactivity is defined by the dust deflagration index, K_{St}, which is calculated from the maximum rate of pressure rise, $(dP/dt)_{\mathrm{max}}$, during a dust explosion in a closed volume, V, using a standard 1 m³ or 20-L vessel [1, 6]:

$$K_{\mathrm{St}} = \left(\frac{dP}{dt}\right)_{\mathrm{max}} V^{1/3}. \quad (1)$$

While this method provides a consistent basis for assessing the relative hazard of combustible dust, it is important to note that the severity of an actual explosion is primarily influenced by the specific dispersion and initiating event, which can significantly affect the level of initial turbulence. As a result, K_{St} alone has been shown to have significant limitations in accurately characterizing historic dust explosion events [7].

Furthermore, these limitations pose challenges when using K_{St} to describe the reactivity of a specific test and the conditions under which it was performed. In non-standard test apparatuses, the level of initial turbulence is often varied by changing the delay between dust injection and ignition to examine a range of explosion severities. Generally, these experiments are characterized by an effective deflagration index, K_{eff}, which is evaluated using Eq. (1) for a specific test condition. It is important to recognize, however, that K_{eff} represents the rate of combustion at a single time, typically late in the combustion process when the flame approaches the vessel walls. As a result, experiments with similar K_{eff} values can produce significantly different rates of pressure rise during the critical early phase, when explosion protection measures are most effective.

Correspondence to: carl.bauwens@fmglobal.com

To address these limitations, a two-parameter model was developed, in a previous study [8], to characterize the full pressure time-history during a closed vessel dust explosion. This model utilizes two parameters: $S_{\mathrm{T},R}$, an effective propagation velocity of the flame's leading edge, and a dimensionless parameter χ, which compares the characteristic time of flame propagation to the characteristic consumption time of the dust within the flame. The previous study focused exclusively on constant volume tests to characterize $S_{\mathrm{T},R}$ and χ, finding that χ is generally a property of the dust itself, while $S_{\mathrm{T},R}$ varies with the level of initial turbulence [8].

The objective of the current study is to examine the effects of the $S_{\mathrm{T},R}$ and χ parameters in a vented configuration, specifically on the maximum rates of pressure rise and peak pressures generated. This work examines three dusts: two with similar χ values and one with a significantly higher χ. In addition, experiments were conducted with two ignition delays to vary $S_{\mathrm{T},R}$ for a given dust, examine how the results scale with the level of initial turbulence.

2 Experimental Setup

A total of 20 vented explosion tests were conducted in a 2.42-m³ vessel with a height-to-diameter ratio of 1.45, as illustrated in Fig. 1a. To ensure a uniform comparison between different dusts at a given ignition delay, a previously developed dual-air cannon dust injection system was employed, as shown in Fig. 1b. Dust was injected into the vessel immediately prior to ignition using two counterflow injection systems, each consisting of two air cannons, a sealed dust hopper, an explosion isolation valve, and an internal dispersion nozzle.

For each injector, two Martin® Hurricane 35-L air cannons, pressurized to 8.3 bar (gauge), were used to independently inject dust and generate turbulence. These air cannons were timed to fire in series with a prescribed 0.5-second delay. The first cannon was used to fully disperse the dust into the vessel, while the second cannon injected air to generate a consistent level of initial turbulence.

Prior to each test, the hoppers were loaded with a prescribed mass of dust, m_{d}, to achieve the target dust loading, $\rho_{\mathrm{DL}} = m_{\mathrm{d}}/V$. The vessel was then evacuated to a specified pressure of approximately 0.5 bar, with slight variations to account for initial gas temperature, resulting in an initial pressure, P_0, of 1.00 ± 0.03 bar after dust and air injection. The ignition system was triggered following a prescribed ignition delay, t_{ign}, measured from the time the second air cannon used for turbulence generation was fired.

Figure 1: Photographs showing a) the 2.42-m^3 test vessel setup and b) the dual air cannon configuration. [8]

The dispersed dust mixture was ignited at the center of the vessel by two 5-kJ Sobbe EBBOS ChZ pyrotechnic ignitors. Internal pressure was measured at three vertical locations within the vessel using Kistler 4260A 0-10 bar piezoresistive pressure transducers, sampling at a rate of 20 kHz.

To ensure tests consistency with the previous constant volume setup, vacuum rated domed vent panels were used. For each test, a nominal 0.61-m diameter round vent (0.55-m actual open area) with a static vent deployment pressure, P_{stat}, of 0.1 bar was installed on the top flange of the vessel. The panels were designed to deploy in a hinged manner to prevent fragmentation, as shown in Fig. 2. The deployed section of a vent panel was weighed following a test, and the panel area density was measured as 15.2 kg/m^2.

Figure 2: A post-test photograph showing a deployed vent panel.

This study examined three dusts, cornstarch, cellulose fiber, and powdered sugar. It should be noted that the powdered sugar contained 3.5% cornstarch by weight as an anti-caking agent. For all the test performed, a dust loading, ρ_{DL}, of 0.75 kg/m^3 was used and two ignition delays, $t_{\mathrm{ign}} = 0.34$ ms and $t_{\mathrm{ign}} = 0.20$ ms, were examined to see the effect of initial turbulence on the same dust. The properties of the dusts, including values of K_{eff} and $S_{\mathrm{T},R}$ obtained in a previous study [**Error! Bookmark not defined.**] for $\rho_{\mathrm{DL}} = 0.75$ kg/m^3, are summarized in Table 1.

Table 1. Properties of the dusts examined.

Dust	d_{50} (μm)	$P_{\max}$ (bar)	χ	t_{ign} (s)	K_{eff} (bar·m/s)	$S_{\mathrm{T},R}$ (m/s)
Cornstarch	14	9.0 ± 0.2	0.12 ± 0.01	0.34	195 ± 12	2.0 ± 0.1
				0.20	310 ± 5	3.0 ± 0.2
Cellulose Fiber	74	7.8 ± 0.1	0.12 ± 0.01	0.34	84 ± 5	1.1 ± 0.1
				0.20	$120^* \pm 5$	$1.6^* \pm 0.1$
Powdered Sugar	17	7.3 ± 0.4	0.31 ± 0.05	0.34	40 ± 6	1.2 ± 0.1
				0.20	68 ± 7	1.9 ± 0.3

*Estimated from constant volume tests that were performed with ρ_{DL} = 0.5 and 1.0 kg/m^3.

For each combination of dust and ignition delay, a minimum of three repeated tests were performed. The vent deployment and external explosion were captured by a Phantom Flex high-speed camera, which was also used to determine the time of vent deployment and the pressure at which it occurred.

3 Results

Figure 3 presents representative images from tests conducted on each of the three dusts, covering the period from vent deployment to 50 milliseconds afterward, by which time the overall maximum overpressure had already been achieved in all tests. Visually, only slight differences were observed between the experiments performed with the different dusts. In general, powdered sugar produced the most transparent clouds and cellulose fiber the most opaque, particularly after the external explosion. Also, the cornstarch experiments produced the strongest external explosions with the largest visible external fireballs.

Figure 3: Images captured by the high-speed camera for tests performed with $t_{\mathrm{ign}} = 200$ ms, for the three dusts presented left-to-right in 10-ms intervals starting from the time of vent deployment.

Pressure time-histories for the three different dusts with lower initial turbulence, $t_{\mathrm{ign}} = 0.34$ s, are compared in Fig. 4a. The solid curves show 100-Hz low-pass filtered pressure averaged across the repeated tests and the shaded regions show the variability across all of the tests performed in that series. Overall, the test-to-test repeatability was quite good for these conditions. It can be clearly seen that the initial rate of pressure rise for the powdered-sugar tests were higher than that of cellulose fiber, with an initial rise quite similar to that of cornstarch, despite having the lowest value of K_{eff}. Examining the rate of pressure rise curve, Fig. 4b, it can also be seen that all of the cornstarch tests had a distinctive double peak structure, which was found to correspond to the time of vent deployment, followed by the time of the external explosion. On the other hand, the maximum rate of pressure rise typically occurred at the time of vent deployment for the cellulose fiber and powdered sugar tests.

Experiments performed with a higher level of initial turbulence, $t_{\mathrm{ign}} = 0.20$ s, are compared in Fig. 5. These tests exhibited similar variability to the those performed with longer ignition delays, except for the cellulose fiber tests. The high test-to-test variability exhibited by the cellulose fiber experiments may have been a result of its lower bulk density slowing the dust injection process prior to the firing the second air cannon, creating a less uniform spatial distribution of dust at the time of ignition. Overall, the higher levels of initial turbulence created larger differences between the powdered sugar and cellulose fiber results for both the peak pressure and the rate of pressure rise, when compared to the tests performed with a longer ignition delay. In addition, the double peak structure in the rate of pressure rise curve for cornstarch merged into a monotonic increase, with only a slight change in slope at the time of vent deployment.

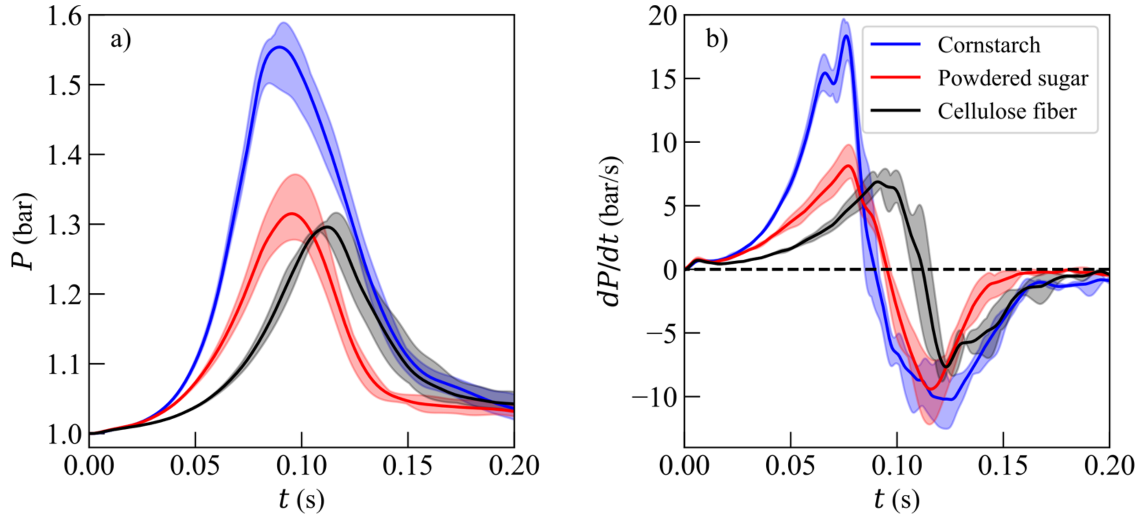

Figure 4: Comparison of a) pressure time-histories and b) rate of pressure rise across the different mixtures with $t_{\mathrm{ign}} = 0.34$ s.

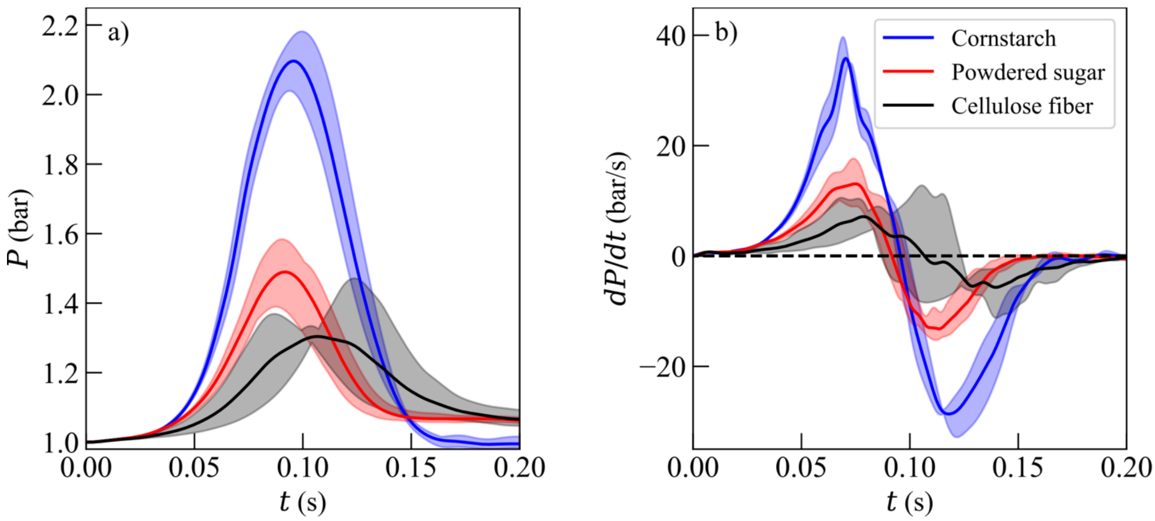

Figure 5: Comparison of a) pressure time-histories and b) rate of pressure rise across the different mixtures with $t_{\mathrm{ign}} = 0.20$ s.

4 Discussion

The effect of the reactivity parameter χ can be clearly seen when comparing P_{red} as a function of the deflagration index K_{eff}, as shown in Fig. 6a. Here we can see that while cornstarch and cellulose fiber follow the same exponential scaling as a function of K_{eff}, the powdered sugar results increase much more rapidly. It is interesting to note, that if the reduced pressure is scaled by the turbulent propagation velocity $S_{\mathrm{T},R}$, all three dusts scale well with a simple exponential fit, as shown in Fig 6b. This is because $S_{\mathrm{T},R}$ is characterizes the initial rate of flame propagation and pressure rise during a dust explosion [8]. These results clearly demonstrate the need to account for χ, or more directly $S_{\mathrm{T},R}$, when designing explosion protection, as the increased rate of initial pressure rise also would affect the performance of active explosion protection devices, like suppression and isolation.

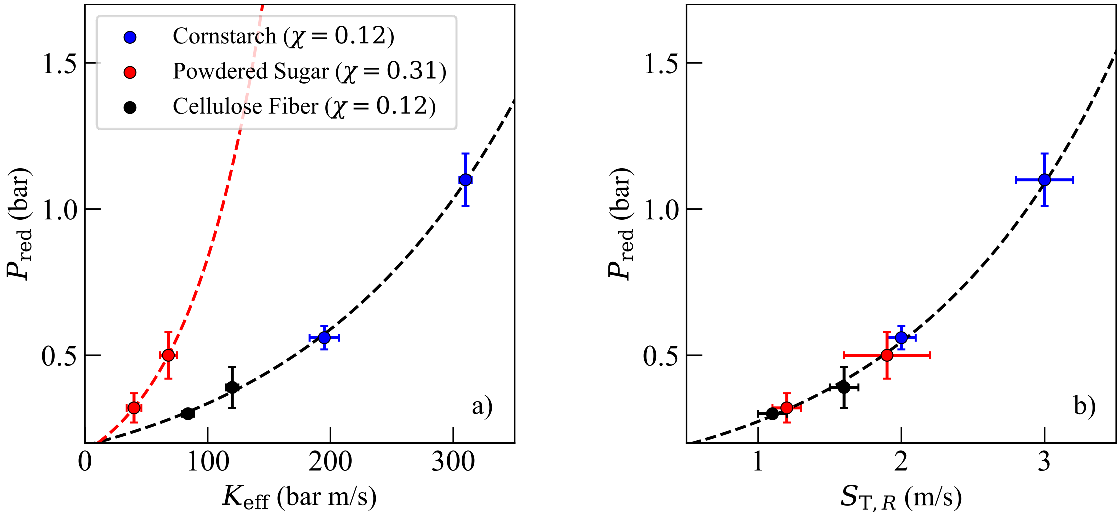

Figure 6: Comparing maximum reduced pressure obtained as a function of a) K_{eff}, and b) $S_{T,R}$, where the dashed lines show a simple exponential fit of the results.

4 Conclusions

This study examined vented dust explosion experiments performed in a 2.42 m^3 vessel, for three dusts with two levels of initial turbulence, to investigate how reduced pressure scales with different reactivity measures. It was found that the peak pressures obtained were highly correlated to the turbulent propagation velocity, $S_{T,R}$, obtained using a two-parameter model, and not with the deflagration index, as K_{eff} does not account for when the maximum rate of pressure rise occurs during the pressure transient. This work clearly demonstrates the limitations of the traditional deflagration index approach for characterizing dust explosions and the importance of improved reactivity measures. Future work will examine what dust material properties are responsible for determining the χ parameter and whether it is possible to predict these values from laboratory scale experiments.

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