Characterizing the Reactivity of Large-Scale Dust Explosions

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1 Introduction

Dust explosions can present a significant hazard at any facility where combustible dusts are present. To mitigate the consequences of these explosions, protection measures, such as explosion venting, suppression and isolation, are commonly deployed. The inherent reactivity of the dust, however, must be considered when designing explosion protection, which can vary significantly between different dusts [1]. To characterize the reactivity of a specific dust, a parameter referred to as the dust deflagration index, K_{st}, is typically used. This deflagration index is an empirical quantity based on the maximum rate of pressure rise, $(dP/dt)_{\max}$ for a vessel volume, V, in a test performed in a standardized test apparatus:

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

To assess the performance of different protective devices, and to develop the guidelines used to protect a specific enclosure, large-scale tests are often conducted. As the level of turbulence at the time of ignition significantly affects the propagation rate of a dust flame and the severity of an explosion [2], the delay between dust injection and ignition is one of the primary factors that determines the strength of a dust explosion experiment.

By convention, the ignition delay used in a large-scale test is typically tuned to produce an effective deflagration index, referred to as K_{eff}, equivalent to the value of K_{st} of a specific class of dust. While the use of K_{st} may be effective for assessing the relative hazard presented by different dusts, it is often inadequate at describing the overall behavior of large-scale dust explosions [3], as it characterizes the reactivity at a single time, typically late in the combustion process when the flame approaches the vessel walls. As a result, experiments performed with consistent values of K_{eff} can produce significantly different rates of pressure rise at the early phase when explosion protection devices are designed to activate.

This study describes a new method to characterize the effective reactivity of large-scale dust explosion experiments by developing a simple model for estimating the pressure rise that

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occurs during a closed volume dust explosion. This method is then compared with large-scale experiments performed in an 8-m^3 vessel.

2 Model Development

For the model described subsequently, turbulent dust flame propagation is considered where the dust within the burning region is consumed over a finite reaction time. The model assumes that the propagation of the leading edge of the flame front is governed by turbulent mixing, which entrains a mixture of unburned dust/air into the flame or burning region. Within this region, which is characterized by an effective flame radius, r_f, the unburned mixture is not consumed instantaneously, and a mixture of burned and unburned dust is present. As typical dust explosions are fuel-rich, the reaction time within the burning region is modeled by considering the consumption rate of the oxidizer using a simple mass balance. The general model formulation is similar to that proposed by Tamanini [4], with a different treatment of the underlying model assumptions, as described below.

The model equations are derived considering mass and energy conservation, consistent with previously developed models [5, 6] for gas flames, where the rate of combustion is evaluated on a mass basis [6]. The mass fraction of oxidizer is split into three quantities that are tracked individually: the unburned mass fraction upstream of the flame, x_u; the unburned mass fraction within the flame region, $x_{f,u}$; and the burned mass fraction of oxidizer within the flame region, $x_{f,b}$. As the total mass of oxidizer is conserved in a closed volume, the mass balance is given by:

$$1 = x_u + x_{f,u} + x_{f,b}. \tag{1}$$

Assuming spherical flame propagation, the rate of change of the unburned mass fraction is governed by the rate at which unburned mass enters the flame region:

$$\frac{dx_u}{dt} = -\frac{3r_f^2 S_T \rho_u^*}{R^3}, \tag{2}$$

where S_T is the turbulent propagation velocity of the leading edge of the flame, ρ_u^* the gas density of the oxidizer in the unburned region normalized by the initial gas density, and R is the effective radius of the vessel, $R = \left(\frac{3V}{4\pi}\right)^{1/3}$. The propagation velocity of the leading edge of the flame is assumed to be governed by turbulent mixing at the scale of the flame radius and is proportional to the turbulent fluctuation velocity at this scale. For a Kolmogorov cascade, this yields an increase of S_T with flame radius due to the increased range of turbulent length scales involved in mixing as the flame grows:

$$S_T = ku' \left(\frac{r_f}{R}\right)^{\frac{1}{3}}, \tag{3}$$

where u' is the turbulent fluctuation velocity at an integral scale and k is a proportionality coefficient. As both the level of initial turbulence, u', and the proportionality factor, k, are not typically known, and are difficult to characterize independently, they are combined into a single reactivity parameter, $S_{T,0} = ku'$, which represents a characteristic turbulent burning velocity. Note that this quantity is specific to a given dust and experimental setup, as it depends on both the dust properties and the level of turbulence present. For the purpose of this model, it is

assumed that $S_{T,0}$ is an effective value that remains constant throughout the explosion. It is also important to note that this model formulation has an intrinsic characteristic time:

$$\tau' = \frac{R}{S_{T,0}}, \tag{4}$$

which is proportional to the time needed for the flame front to reach the vessel boundary. To generalize the solution to various vessel sizes, one can define a dimensionless time, $t^* = \frac{t}{\tau'}$, and a dimensionless flame radius, $r_f^* = \frac{r_f}{R}$. In dimensionless terms, Eq. (2) becomes:

$$\frac{dx_u}{dt^*} = -3{r_f^*}^{7/3}\rho_u^*, \tag{5}$$

The accumulation of unburned mass within the flame region depends on the balance between the rate at which upstream gas enters the flame region, and the rate unburned gas within the flame region is consumed:

$$\frac{dx_{f,u}}{dt^*} = 3{r_f^*}^{7/3}\rho_u^* - \frac{dx_{f,b}}{dt^*},\ r_f^* < 1 \tag{5}$$

$$\frac{dx_{f,u}}{dt^*} = -\frac{dx_{f,b}}{dt^*},\ r_f^* = 1. \tag{6}$$

For the conditions typically present in a dust explosion, it can be shown that both the Taylor and Kolmogorov scales of turbulence significantly exceed the dust particle radii, and the local transport of fuel and oxidizer in the vicinity of the particle are in the laminar regime. As a result, it is assumed that the consumption rate of the oxidizer is governed by molecular diffusion and the dust properties, and the consumption rate is proportional to both the dust concentration and the molecular diffusion coefficient:

$$\frac{dx_{f,b}}{dt^*} = \frac{\tau'}{\tau}\frac{{T_f^*}^{1.75}}{P^*}\left(\frac{x_{f,u}}{x_{f,u}+x_{f,b}}\right), \tag{7}$$

where τ is a characteristic burning time, which is dependent on various dust material properties, such as particle size and the molecular diffusion coefficient; P^* is the vessel pressure normalized by the initial pressure; and T_f^* is the average temperature within the flame region normalized by the initial temperature. The pressure and temperature dependence of the diffusion coefficient is explicitly retained in Eq. (7) such that the characteristic time τ is invariant to the change in pressure and temperature that occurs during a constant volume dust explosion. The average temperature within the flame region is approximated as:

$$T_f^* \approx \frac{\sigma x_{f,b}+x_{f,u}}{x_{f,b}+x_{f,u}}, \tag{8}$$

where the expansion ratio σ is the ratio of unburned to burned gas density at ambient pressure, estimated as $(P_\mathrm{m}-1)/P_0$, where P_m is the constant volume explosion pressure.

Assuming isentropic compression, the unburned and burned gas densities at a given pressure can be expressed as:

$$\rho_u^* = {P^*}^{\frac{1}{\gamma_u}},\quad \rho_b^* = \frac{1}{\sigma}{P^*}^{\frac{1}{\gamma_b}} \tag{9}$$

where γ_u and γ_b are the unburned and burned specific heat capacity ratios, respectively. As these values are poorly defined for a dust/air mixture, it is assumed that $\gamma_u = \gamma_b = \gamma'$ to simplify the calculation, where γ' is an effective specific heat ratio. The value of γ' that yields the correct constant volume explosion pressure, P_{m}, and expansion ratio is calculated using the following expression [6]:

$$\gamma' = \frac{\log(P/P_{\mathrm{m}})}{\log(1/\sigma)}. \tag{10}$$

To evaluate the instantaneous vessel pressure from the mass balance within the enclosure, we first note that the total vessel volume is constant:

$$1 = \frac{x_{f,b}}{\rho_b^*} + \frac{x_u + x_{f,u}}{\rho_u^*}, \tag{11}$$

and Eqs. (9) and (11) can be combined to yield the following expression for the normalized pressure:

$$P^* = \left[(\sigma - 1)x_{f,b} + 1\right]^{\gamma'} \tag{12}$$

The flame radius is then obtained from the flame volume, $V_f^* = \frac{x_{f,b}}{\rho_b^*} + \frac{x_{f,u}}{\rho_u^*}$:

$$r_f^* = \left(1 - \frac{x_u}{(\sigma-1)x_{f,b}+1)}\right)^{1/3}. \tag{13}$$

In dimensionless terms, a single parameter, $\chi = \frac{\tau}{\tau'}$, representing the ratio of consumption to propagation time, characterizes the overall behavior of the model, as shown in Fig. 1. Although the general solution depends on this parameter, any comparison with experimental data requires converting the time and length scales through $V^{1/3}$, $S_{T,0}$ and σ. The model suggests that, for a given shape of the pressure rise curve, the maximum rate of pressure rise scales with $V^{1/3}$, which is consistent with the volume scaling of K_{st} and K_{eff}.

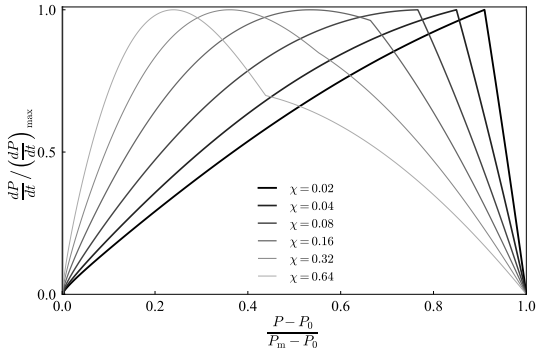

Figure 1: Generalized model results as a function of normalized pressure for a range of the dimensionless parameter, χ.

3 Results and Discussions

To illustrate the performance of the dust combustion model, a comparison is made with closed volume dust explosion experiments performed in an 8-m^3 vessel with a height-to-diameter ratio of 1.45, shown in Fig. 2, as described in previous studies [5, 7].

Figure 2: Image of the 8-m^3 test vessel showing the location of two dust injectors.

Representative model results are compared with experimental data in Fig. 3 (left), for two dusts, powdered sugar and cornstarch, where the ignition delay was tuned to produce similar values of the maximum rate of pressure rise, and the deflagration index K_{eff}. This figure illustrates how two tests with the same value of K_{eff} can produce significantly different pressure rise profiles and how the two-parameter model can effectively reproduce the rate of pressure rise and characterize the overall shape of the pressure profile.

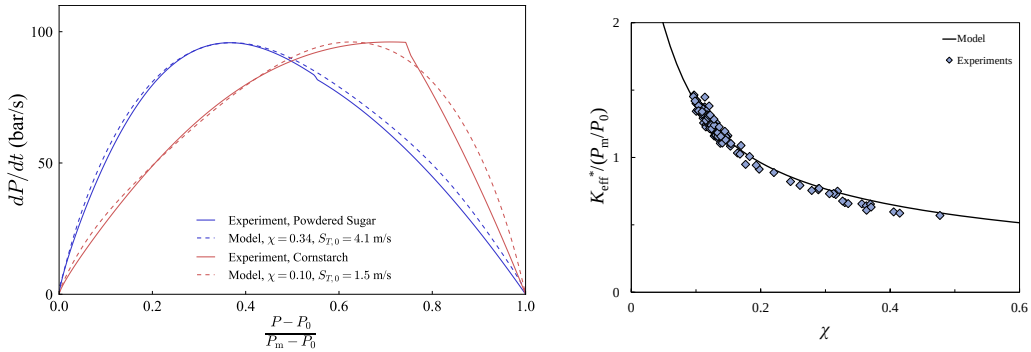

Figure 3: Illustrative model comparison with cornstarch and powdered sugar experiments performed in an 8-m^3 vessel (left) and the variation of K_{eff}^* as a function of parameter χ (right).

A dimensionless dust deflagration index, K_{eff}^*, can also be defined relating the overall maximum rate of pressure rise, analogous to K_{eff}:

$$K_{\text{eff}}^* = \frac{K_{\text{eff}}}{\sigma P_0 S_{T,0}}.$$

This dimensionless dust deflagration index was compared with 164 large-scale experiments performed in the 8-m^3 vessel over a wide range of ignition delays, for several different dusts, and at different dust loadings, and the results are shown in Fig. 3 (right). A monotonic

relationship between the dimensionless dust reactivity parameter K_{eff}^{*} and the dimensionless parameter χ was found, where the maximum rate of pressure rise decreases with χ for a given value of $S_{T,0}$. These results show good agreement between the model and experiments when the values of K_{eff}^{*} and χ were fitted to each experimental pressure profile.

5 Conclusions

In this study, a dust-flame combustion model is developed based on a characteristic turbulent burning velocity and a finite reaction time. It was found that the model can reproduce the overall shape of the experimental rate of pressure rise observed in a wide range of experiments performed in an 8-m^3 vessel. The model suggests that, for a given value of the parameter χ, the ratio of consumption to propagation time, the maximum rate of pressure rise scales with $V^{1/3}$, which is consistent with the volume scaling of K_{st} and K_{eff}.

The results also showed that the shape of the rate of pressure rise curve can vary significantly for experiments performed in the same apparatus, where the maximum rate of pressure rise can occur at considerably different pressures in tests producing the same effective deflagration index. This demonstrates how the use of a single parameter, such as K_{eff}, is insufficient to characterize the behavior of large-scale explosions and how a better method is needed to characterize dust explosions.

With this model, equivalency between different experimental setups can be established by fitting the model parameters $S_{T,0}$ and χ to the measured pressure profiles. Furthermore, this model can also provide a basis for future methods of explosion hazard evaluation that consider the level of initial turbulence and the material properties of the specific dust present.

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