Dynamics of Hybrid-Mixture Explosions at Large Scales

Lorenz R. Boeck, C. Regis L. Bauwens, Sergey B. Dorofeev
FM Global, Research Division
Norwood, MA, USA

1 Introduction

Reactive mixtures of flammable gases with combustible dusts and oxidizer, commonly referred to as hybrid mixtures, pose severe explosion hazards in industries such as mining, power generation, pharmaceutical, agriculture and food, and other manufacturing [1]. Developing risk assessment methods and explosion prevention/protection solutions requires knowledge of explosion sensitivity and severity parameters for these mixtures, and an understanding of explosion dynamics at realistic industrial scales. In particular, large-scale tests are needed since combustion in the small-scale tests apparatuses commonly used to characterize hybrid mixtures, such as the 20-L sphere, is often dominated by ignition and wall effects. This work presents the results of hybrid-mixture explosion experiments conducted in an 8-m^3 vessel and discusses explosion reactivity parameters including maximum explosion pressure, deflagration index, and turbulent burning velocity. Novel insight is gleaned on the effect of mixture composition on these parameters and the overall explosion dynamics.

2 Methodology

The experiments presented in this work were performed using an 8-m^3 explosion test vessel located at the FM Global Research Campus in West Glocester, RI, USA. The vessel was equipped with systems for gas supply and dust injection, see Figure 1, which allowed for creating gas-air, dust-air, and gas-dust-air (hybrid) mixtures. In this study, hybrid mixtures composed of propane (C_3H_8) and cornstarch dust (CS) were examined. All experiments were conducted at ambient initial pressure and under consistent turbulent initial conditions, *i.e.*, initial turbulence was generated by injecting air for gas tests and dust/air for dust or hybrid tests, maintaining the same air injection pressure and delay between injection and ignition. The ignition delay was chosen such that explosions of CS-air at optimum dust concentration (750 g/m^3) produced an effective deflagration index of $K_{\mathrm{eff}} \approx 200$ bar·m/s, representing an often-used reference condition that signifies the upper bound of the St-1 dust reactivity class and is reasonably close to $K_{\mathrm{St}} \approx 160$ bar·m/s of the CS dust measured in ASTM E1226 tests. Two chemical igniters (Sobbe 5 kJ) were placed at the vessel center to achieve ignition, which is a

Correspondence to: lorenz.boeck@fmglobal.com

common ignition source used in both laboratory-scale and large-scale dust explosion testing. Further details on the experimental setup and procedure are given in [2].

Experiments were conducted with pure C_3H_8-air mixtures (0 g/m^3 CS), mixtures of C_3H_8 with a low concentration of CS (100 g/m^3 CS), and C_3H_8 with optimum concentration of CS (750 g/m^3 CS). Two experiments were performed for each condition.

The vessel pressure, P, was measured using three redundant Kistler 4260A transducers, and the recorded pressure traces were analyzed to determine the maximum explosion pressure, P_{max}, and the effective deflagration index, $K_{eff} = (dP/dt)_{max}\, V^{1/3}$.

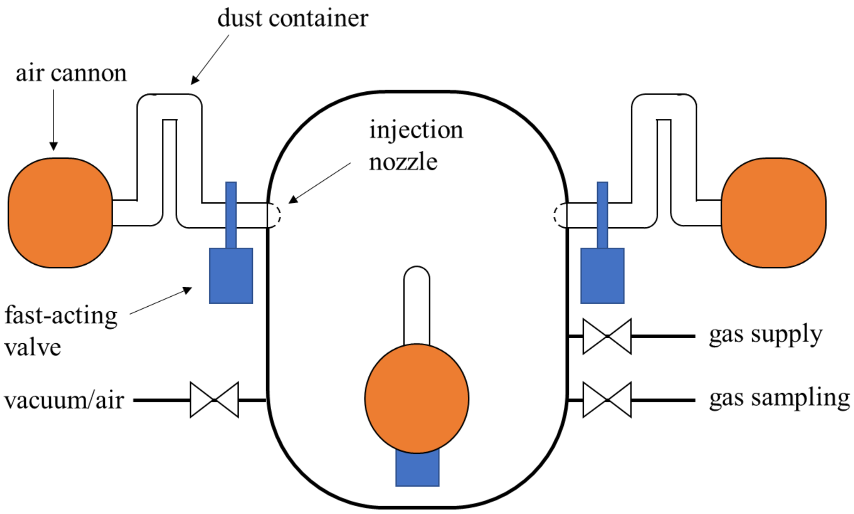

Figure 1: Schematic of 8-m^3 explosion vessel with gas supply and dust injection systems.

Furthermore, a spherical-flame model was used to infer effective turbulent burning velocities, S_{eff}, from the pressure histories. This model considers mass balances for unburned (subscript u) and burned (subscript b) gas in a closed vessel with volume V,

$$\frac{dm_\mathrm{u}}{dt} = -S_\mathrm{eff}\rho_\mathrm{u}A_\mathrm{f};\ \frac{dm_\mathrm{b}}{dt} = S_\mathrm{eff}\rho_\mathrm{u}A_\mathrm{f};\ V = \frac{m_\mathrm{b}}{\rho_\mathrm{b}} + \frac{m_\mathrm{u}}{\rho_\mathrm{u}}, \tag{1}$$

where the unburned and burned gas densities are obtained from

$$\rho_u = \rho_0\left(\frac{P}{P_0}\right)^{1/1.4};\ \rho_\mathrm{b} = \rho_0\left(\frac{P}{P_\mathrm{max}}\right)^{1/\gamma^*}. \tag{2}$$

The effective isentropic exponent for burned gas, γ^*, is given by

$$\gamma^* = \frac{\log\left(P_0/P_\mathrm{max}\right)}{\log\left(1/\sigma_0\right)}, \tag{3}$$

using the initial expansion ratio, σ_0, which can be taken from equilibrium calculations or estimated as $\sigma_0 \approx (P_{max}-P_0)/P_0$, where P_{max} and P_0 are the maximum explosion pressure and initial pressure, respectively. The effective turbulent burning velocity, S_{eff}, is optimized such that the experimental pressure trace is reproduced at minimum root-mean-square error within a defined pressure range.

3 Results and Discussion

Parameters commonly used to characterize the reactivity of combustible dusts and hybrid mixtures for engineering purposes include the deflagration index, K, and the maximum explosion pressure, P_{max}. These parameters were determined for the large-scale experiments conducted in the present work and are summarized in Figure 2, as a function of volumetric C_3H_8 concentration, X_{C3H8}. The deflagration index is referred to as the "effective" deflagration index, K_{eff}, since experiments were conducted in a non-standard experimental setup.

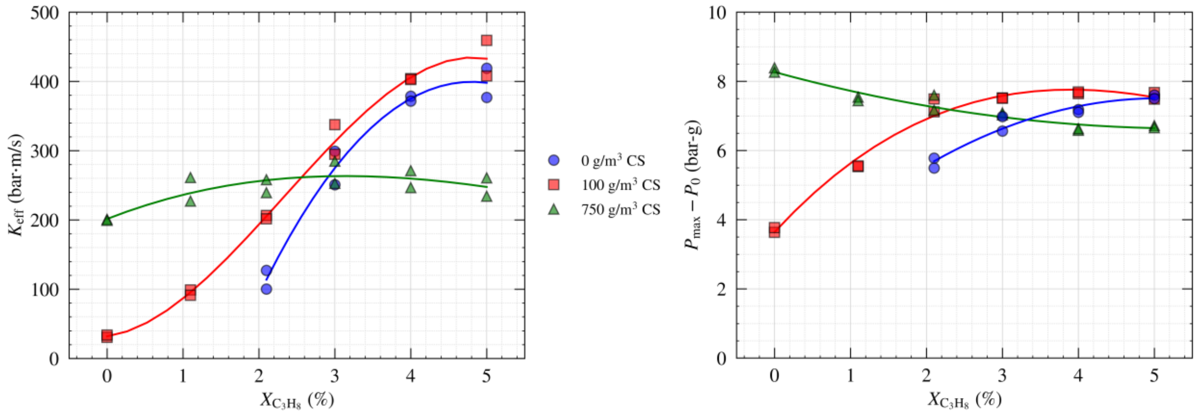

Figure 2: Effective deflagration indices (left) and maximum explosion pressures (right).

Pure CS at 750 g/m^3 exhibits $K_{eff} \approx 200$ bar·m/s, and a moderate increase in K_{eff} occurs with increasing X_{C3H8}, peaking at X_{C3H8} = 3% and 253–285 bar·m/s and decreasing toward higher X_{C3H8}. Experiments at 100 g/m^3 CS show a strong increase in K_{eff} with increasing X_{C3H8}, from 30–34 bar·m/s at X_{C3H8} = 0% to 407–459 bar·m/s at X_{C3H8} = 5%. Mixtures with 100 g/m^3 CS exceed the deflagration indices of pure gas mixtures across the range of tested X_{C3H8}. At 100 g/m^3 CS and X_{C3H8} = 5%, where the overall highest values of K_{eff} occur, K_{eff} exceeds the value for pure gas by 9%. The high reactivity of this hybrid mixture is driven by the gas component with a comparably small contribution from CS. Figure 2, right panel, summarizes P_{max} values. At 750 g/m^3 CS, addition of C_3H_8 leads to a decrease in P_{max}, whereas at 100 g/m^3 CS, addition of C_3H_8 increases P_{max}. Likewise, P_{max} increases for pure gas mixtures with increasing X_{C3H8}. The peak value of P_{max} occurs at 750 g/m^3 CS and X_{C3H8} = 0%.

While values of P_{max} provide useful information on the energetics of hybrid mixtures, values of K_{eff} can be misleading when attempting to characterize the rate of combustion during an explosion. This becomes apparent when examining pressure histories, see Figure 3, left column. In each figure, shaded areas represent the spread between the two repeated tests conducted for each condition, and solid lines represent the average. Results for K_{eff} alone would suggest a higher rate of combustion in hybrid mixtures of C_3H_8 and 100 g/m^3 CS compared to pure C_3H_8 at all investigated X_{C3H8}. In particular, K_{eff} results would indicate that the most reactive investigated mixture is composed of 5% C_3H_8 and 100 g/m^3 CS. By contrast, pressure histories show an overall faster pressure rise for pure C_3H_8 at both X_{C3H8} = 4% and X_{C3H8} = 5%.

An insightful depiction of explosion dynamics is obtained when plotting the rate of pressure rise, dP/dt, as a function of normalized pressure, $\Pi = (P–P_0)/(P_{max}–P_0)$, see Figure 3, right column. For X_{C3H8} = 4%, dP/dt values are similar between pure C_3H_8 and the hybrid mixture with 100 g/m^3 CS at $\Pi \leq 0.45$, and only deviate at $\Pi > 0.45$. The higher observed value of K_{eff}

for the hybrid mixture is due to faster combustion late in the explosion process, where the flame is large compared to the vessel size. In this phase, the hybrid mixture burns at a higher rate and produces its maximum dP/dt at higher Π than the pure gas mixture. At X_{C3H8} = 5%, dP/dt in pure C_3H_8 exceeds that of the hybrid mixture with 100 g/m^3 CS at low Π, until a reversal occurs at Π ≈ 0.4, again leading to higher K_{eff} for the hybrid mixture due to faster late combustion.

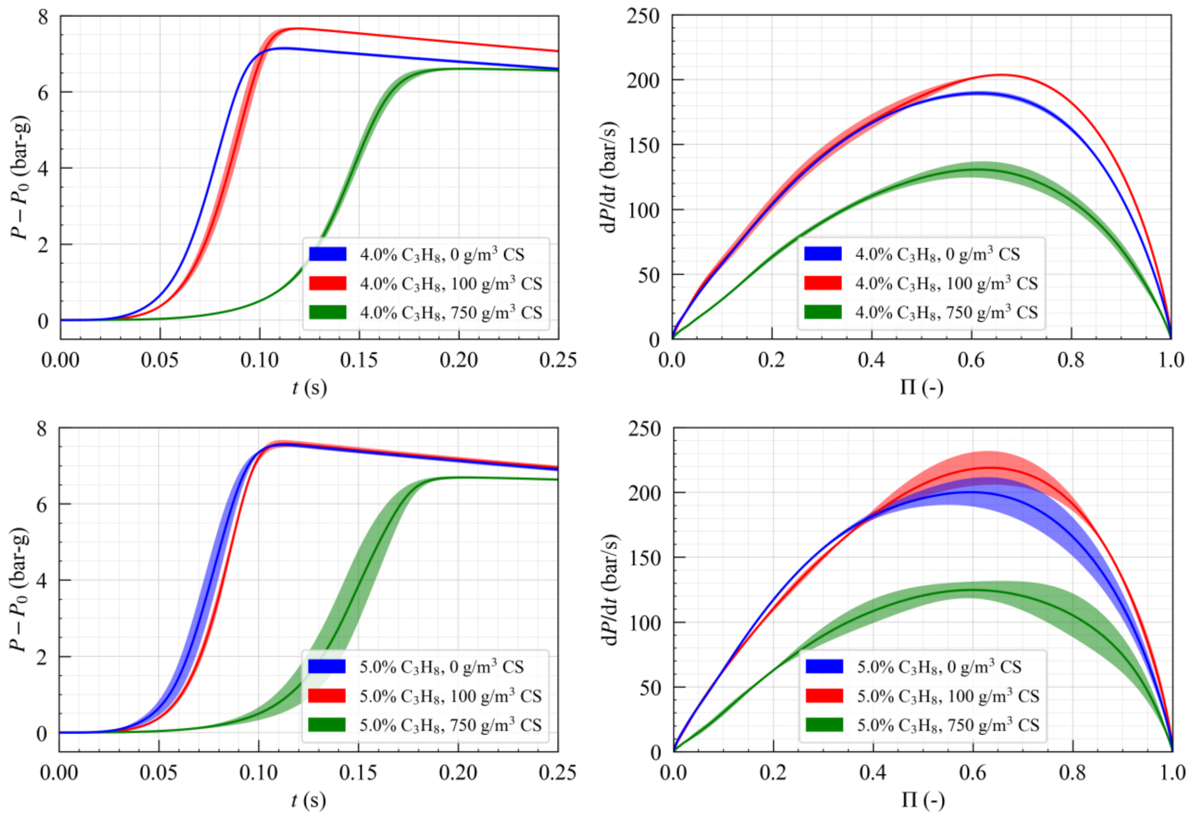

Figure 3: Pressure (left) and rate-of-pressure-rise (right) histories of hybrid-mixture explosions.

To examine the early phase of flame propagation, in contrast to the late phase characterized by K_{eff}, effective turbulent burning velocities S_{eff} were inferred from the experiments, as described in Section 2, and are presented in Figure 4. The fit between spherical-flame model and experiments was optimized in four different intervals of Π, where values of Π close to zero and one represent early and late combustion, respectively. Values of S_{eff} generally vary during the course of flame propagation in a closed vessel due to effects of turbulence and flame instability, finite flame thickness, precompression of reactants, and heat loss to the vessel walls and flame quenching.

The trends in S_{eff} between different mixtures are qualitatively similar to the trends in K_{eff}: Mixtures with 750 g/m^3 CS show the weakest sensitivity to X_{C3H8}, whereas pure C_3H_8 and mixtures with 100 g/m^3 CS are more sensitive. Addition of C_3H_8 affects S_{eff} values of hybrid mixtures differently during the early and late phases of combustion. Early combustion, Figure 4 (a), is less sensitive to X_{C3H8} than later phases, Figures 4 (b–c). Most mixture compositions show an increase in S_{eff} from (a) to (c) and a slight decrease toward (d). During early combustion at low Π, Figure 4 (a), pure gas mixtures with 4–5% C_3H_8 yield the overall highest values of S_{eff}, which corresponds to the fast initial pressure rise observed in Figure 3, compared to hybrid mixtures with CS. Also at higher Π, Figures 4 (b–d), the highest values of S_{eff} are observed for pure gas mixtures rather than for mixtures with CS, but differences are reduced.

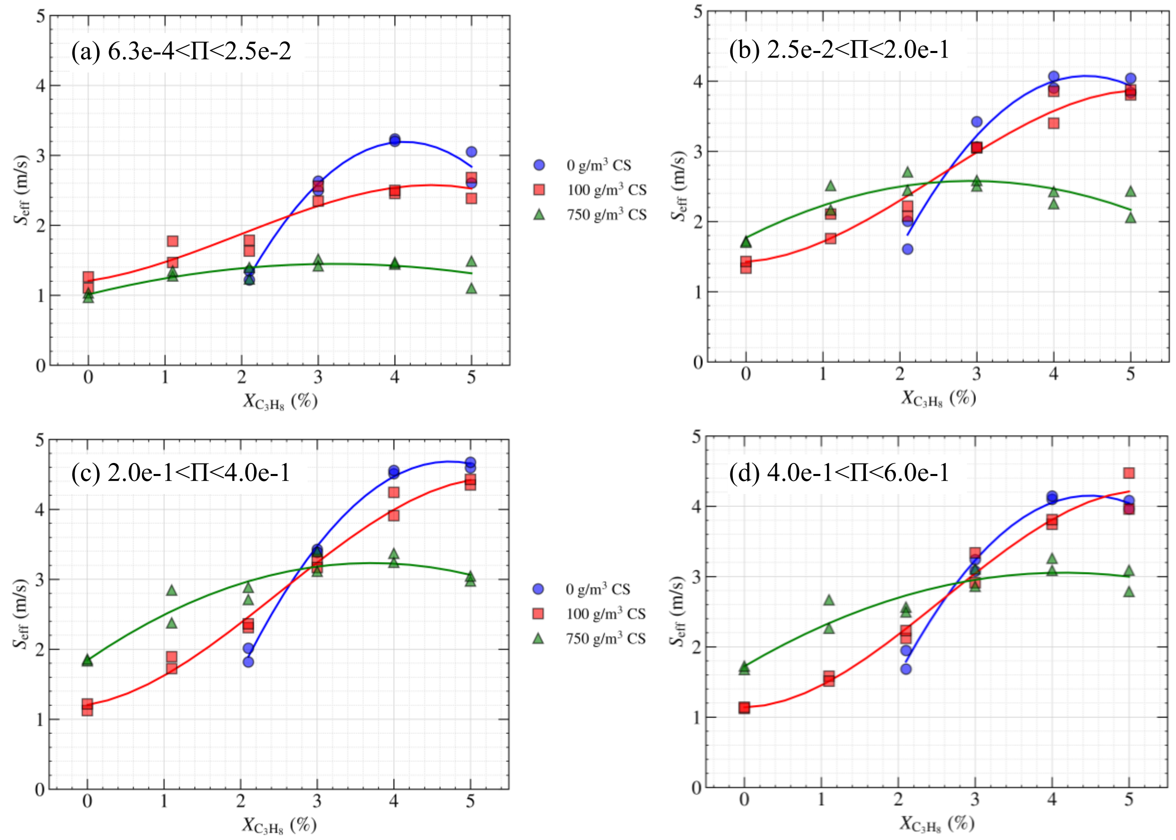

Figure 4: Effective turbulent burning velocities inferred from pressure histories in ranges of (a) 6.3e-4<Π<2.5e-2; (b) 2.5e-2<Π<2.0e-1; (c) 2.0e-1<Π<4.0e-1; (d) 4.0e-1<Π<6.0e-1.

Combining the results from K_{eff}, P_{max}, $P = f(t)$, $dP/dt = f(\Pi)$, and S_{eff} analyses provides novel insight into the dynamics of hybrid-mixture explosions at large scales, compared to pure gas or dust explosions. Several aspects are highlighted:

The composition of hybrid mixtures affects not only their conventional reactivity parameters K and P_{max}, but also their detailed large-scale explosion dynamics. K, indeed, can be a misleading metric since it only describes the maximum rate of combustion at late times, while the dynamics at early times can substantially differ from the trends suggested by K.

The highest values of K_{eff} were observed in mixtures with near-stoichiometric gas composition (4–5% C_3H_8) and low dust concentration (100 g/m^3 CS), see Figure 2. This finding is consistent with small-scale studies that have suggested, based on K measurements, that hybrid mixtures with low dust concentrations may present worst-case mixtures from an explosion hazard perspective, exceeding the K values of pure gas mixtures [3]. Several mechanisms have been proposed to explain this exceedance, including increased turbulence in the presence of dust in typical experimental apparatuses [3,4]; flame wrinkling by dust particles [3]; and radiative pre-heating of dust ahead of the flame [3,5]. In the present experiments, the exceedance in K for hybrid mixtures (4–5% C_3H_8; 100 g/m^3 CS) is produced specifically due to faster combustion at late times, when pressure is high ($\Pi > 0.4$) and the flame is large compared to the vessel size.

At early times (low Π), by contrast, combustion is slower than in pure gas mixtures, suggesting that the investigated hybrid mixtures are not inherently more reactive than the pure gas mixtures. Increased turbulence, flame wrinkling, or continuous radiative pre-heating would lead to uniformly faster combustion also at low Π; hence, these mechanisms do not appear to be responsible for the exceedance in K in the present experiments. Modifications of burning rate or heat transfer at high Π, when flame-wall interactions limit the overall rate of combustion in the vessel and the resulting maximum rate of pressure rise, may explain the differences observed at late times. Additional research is needed to examine these phenomena. From an applied perspective, the differences in reactivity parameters between the most reactive investigated hybrid and pure gas mixtures are relatively small, suggesting that the gas explosion mainly drives the hazard with relatively small contributions from the dust.

4 Concluding Remarks

This study presented novel large-scale experiments on hybrid-mixture explosions. The results show how the hybrid-mixture composition significantly affects explosion dynamics, and demonstrate that conventional reactivity parameters, especially the deflagration index K, are inadequate to capture these effects. In particular, if K alone were used to specify reactivity, it would identify mixtures with low dust concentrations and near-stoichiometric gas concentrations as the most reactive mixtures, which would pose the most severe explosion hazards. Examinations of the entire explosion process, however, revealed that these mixtures are not universally more reactive. In fact, they showed consistently lower turbulent burning velocities than pure gas mixtures during the early combustion process, a critical time where protection systems typically activate and mitigate an explosion. It is only at late times where combustion rates exceeded those of pure gas mixtures, which was ultimately responsible for the higher deflagration indices. These results demonstrate how a differentiated characterization of hybrid-mixture explosion dynamics can improve explosion risk assessment and the design of explosion protection systems. Models used to design such systems would benefit from an accurate description of the early explosion dynamics, which cannot be achieved using conventional reactivity parameters such as the deflagration index.

References

[1] Eckhoff RK. (2003). Dust explosions in the process industries. Gulf Professional Publishing.

[2] Boeck LR, Bauwens CRL, Dorofeev SB. (2022). Hybrid-mixture explosions: Large-scale testing and estimation of reactivity parameters. 10th ISFEH, Oslo, Norway.

[3] Spitzer S, Askar E, Geoerg P, Gabel D, Krause U, Krietsch A. (2022). The maximum rate of pressure rise of hybrid mixtures. 14th ISHPMIE, Braunschweig, Germany.

[4] Banhegyi M, Egyedi J. (1983). Method for determining the explosive limits of a mixture of coal dust, methane and inert matter. International Conference of Safety in Mines Research Institutes, Sheffield, UK.

[5] Ivanov MF, Kiverin AD, Liberman MA. (2015). Ignition of deflagration and detonation ahead of the flame due to radiative preheating of suspended micro particles. Comb. Flame 162:10, 3612-3621.