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Evaluating regime diagrams for closed volume hybrid explosions

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ABSTRACT

Hybrid mixtures of combustible dust and flammable gas represent an enhanced industry hazard due to increased explosion severity over that for the constituent fuels at their given concentrations. The current investigation extends the understanding of hybrid explosion dynamics by identifying and evaluating new explosion regimes on the dust/gas concentration plane. This work builds on previous studies that identified five regimes: gas-driven explosion, dual-fuel explosion, dust-driven explosion, synergic/synergistic explosion, and no explosion. For low ignition energy (e.g., spark ignition) the gas-driven and dual-fuel regimes are extended to include: gas-only explosion, two-stage explosion, single-stage explosion, and dust-only explosion. For high ignition energy (e.g., 10-kJ ignitors) the hybrid behaviour in the dust-driven regime depends on the dust reaction mechanism. For heterogeneous combustion, addition of flammable gas has a minor impact on explosion parameters. For homogeneously reacting dust, two new regimes are proposed: isolated particle combustion close to the dust flammability limit and group combustion further away. It is hypothesized that flammable gas addition has a larger impact in the isolated regime, as the gas acts to bridge individual diffusion flames during flame propagation and explosion. Ongoing research is investigating this hypothesis and reviewing the use of Computational Fluid Dynamics to close the gaps in understanding for hybrid explosion systems.

1. Introduction

Hybrid explosion systems contain combustible dust mixed with flammable gas and can arise in several industries including mining (Amyotte et al., 1993a), pharmaceutical (Hossain et al., 2014), and textile manufacturing (Marmo, 2010). Upset conditions can also lead to flammable vapour build-up in the vicinity of dust sources, and can result in particularly devastating explosions such as that which occurred at the Westray coal mine in 1992 (Amyotte and Oehmen, 2002), and more recently at the Hoeganaes iron powder facility in 2011 (U.S. Chemical Saftey and Hazard Investigation Board, 2011). Previous research has shown a reduction in the flammability limits of hybrid mixtures when compared to single-phase mixtures, and an increase in explosion severity (Bartknecht, 1989; Amyotte et al., 1993b). The increased risk associated with hybrid mixtures makes understanding the explosion dynamics of this system an important research area for prevention and mitigation.

Recent investigation of hybrid mixtures has focused on developing "Explosion Regime Diagrams" for the laboratory scale 20-L testing apparatus (Garcia-Agreda et al., 2011; Sanchirico et al., 2011). In these diagrams, explosion parameters maximum pressure (P_m) and maximum rate of pressure rise (K_m) for individual tests are plotted on the dust concentration/gas concentration plane. Five explosion regimes have been identified in the literature using these diagrams (Garcia-Agreda et al., 2011; Sanchirico et al., 2011): gas-driven explosion; dual-fuel explosion; dust-driven explosion; synergic/synergistic explosion; and no explosion.

The objective of the current work is to review experimental data from the literature in terms of explosion regime diagrams, and to identify and evaluate new regimes that fall under or may replace the existing categories. The focus of this work is on laboratory scale closed volume testing using the 20-L chamber. Specific attention is given to conditions of low ignition energy which may occur in industries that are actively protecting against dust explosion, but may not be prepared for a hybrid explosion event, and high ignition energy as used to determine explosion parameters for equipment protection and venting. In addition to characterising new explosion regimes, the results from this study are also being used to guide numerical modelling efforts being undertaken by the author group

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using Computational Fluid Dynamics (CFD), and to provide insight into theoretical models that may be available.

The remainder of the paper is laid out as follows: Section 2 outlines the existing explosion regimes originally proposed in the literature; Section 3 reviews the available hybrid explosion data and describes the coverage obtained for low ignition energy and high ignition energy, respectively; Section 4 presents an evaluation of additional explosion regimes for low ignition energy; Section 5 present an evaluation of additional explosion regimes for high ignition energy; Section 6 gives a summary and discussion of the overall results; and lastly, Section 7 gives the final conclusions.

2. Explosion regime diagrams

Plotting hybrid explosion data as a regime diagram was first proposed by Garcia-Agreda et al. (2011) and further investigated experimentally by Sanchirico et al. (2011) and theoretically by Russo et al. (2012). Fig. 1 presents the hybrid explosion diagram originally analysed by Garcia-Agreda et al. (2011) for niacin/methane mixtures, using spark ignition and high turbulence levels. These authors normalized the dust concentration axis by the dust Minimum Explosion Concentration (MEC) and the gas concentration axis by the gas Lower Flammability Limit (LFL). They then divided the diagram into five regimes depending on which fuel was above its respective flammability criteria: gas-driven explosion; dust-driven explosion; dual-fuel explosion; synergic/synergistic explosion; and no explosion. Note that the actual data in Fig. 1 was taken from the appendices B.1, B.4, and B.6 of Garcia-Agreda (2010) and differ slightly from that presented by Garcia-Agreda et al. (2011).

Although much research has been devoted to explosion limits of hybrid mixtures (i.e., the no explosion and synergistic regimes, see Khalili et al. (2012), Addai et al. (2015), and Jiang et al. (2015), for example) there are still many unanswered questions in this area. The current research focuses on the dust-driven, gas-driven, and dual-fuel areas of the diagram in hopes that the regimes identified will be useful in later work to characterize explosion limits.

The current work also focuses on low ignition energy and high ignition energy conditions. From the literature data presented in the following section these have been classified as explosions using spark ignition and 10-kJ chemical ignitors, respectively. These represent important limits for industry where low energy ignition may occur for facilities actively protecting against dust explosion but not prepared for a hybrid explosion, and high energy ignition represents worst-case conditions necessary for explosion mitigation and protection design.

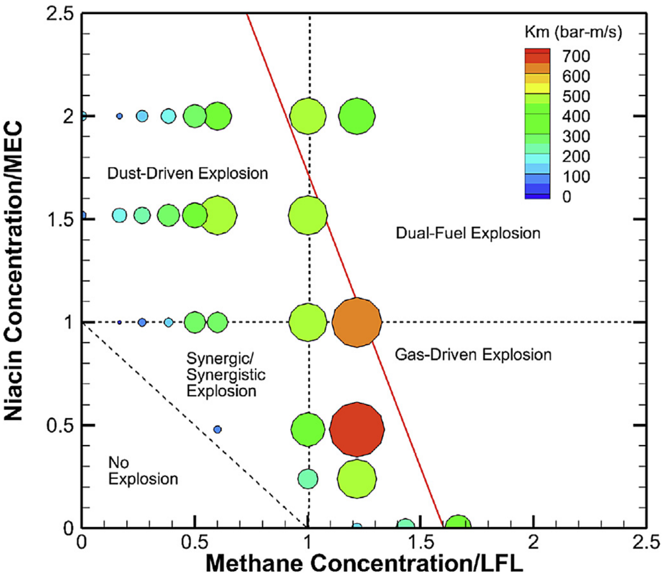

Fig. 1. Hybrid explosion regimes originally proposed by Garcia-Agreda (2010) and Garcia-Agreda et al. (2011) in their work with niacin/methane mixtures and spark ignition.

Although turbulence level and particle diameter play an important role in explosion severity (Eckhoff, 2005), their effects will not explicitly be explored here. Where possible, experimental data using a 60 ms ignition delay time will be investigated in order to evaluate regimes at the typical turbulence level for standardized dust explosion testing. Studies analysing the same dust across a broad spectrum of hybrid concentrations and at different particle diameters could not be found. A difficulty here is the physical amount of dust required to explore extended areas of the regime diagram and the number of tests required. CFD will be used as a tool in future research to explore the full dust/gas concentration plane at reduced time and capital cost when compared to experimental testing.

3. Literature coverage

Experimental data from the literature has been summarized and plotted on the dust/gas plane to show the coverage available for regime diagram analysis. Table 1 gives a summary of explosion data with the dust, gas, ignition energy and ignition delay time used. In cases where experimental parameters were varied, “multiple” is entered in the table. These cases are detailed in the following paragraphs. A review of the individual findings from each study can be found in several papers including those by Ajrash et al. (2016) and Sanchirico et al. (2011).

In their work, Dufaud et al. (2009) presented experimental data for hybrid mixtures of magnesium stearate/ethanol, niacin/diisopropyl ether, and antibiotic dust/toluene, and demonstrated nonlinear additive effects for hybrid explosion. On the other hand, Amyotte et al. (2009) analysed experimental data for fibrous polyethylene mixed with ethylene, hexane, and propane, and found that K_{St} (the maximum K_m in the dust concentration range under standard testing conditions) scaled linearly for the gas concentrations investigated. Hossain et al. (2014) investigated mixtures of lactose and micro crystalline cellulose (MCC) with methanol, ethanol, and isopropanol, and found a difference in the enhancement effects whether the dust was prewetted with the solvent or vaporized in the atmosphere prior to the explosion. The differences in reported outcomes in these three studies show the complexity of hybrid explosion dynamics and demonstrate a need for further research.

Broadly speaking, most hybrid studies presented in Table 1 used the standard dust explosion ignition delay time with the exception of Garcia-Agreda et al. (2011), Sanchirico et al. (2011), Di Benedetto et al. (2012), and Kosinski et al. (2013), who used a range of ignition delay times including 0, 30, 60, 120 ms, and longer depending on the tests. In terms of ignition energy, Di Benedetto et al. (2012) presented results with spark, 0.5 kJ, 1 kJ, and 10 kJ energies, and Ajrash et al. (2016) presented results at 1 kJ, 5 kJ, and 10 kJ.

The studies presented in Table 1 can generally be broken into two groups: those that used spark ignition and those that used high strength chemical ignitors. The concentration ranges covered for spark ignition and 10-kJ chemical ignitors, respectively, are plotted in Fig. 2 and Fig. 3. The axes in these plots have not been normalized, so that the data can also be compared relative to the optimum dust and stoichiometric gas concentrations.

Starting with spark ignition energy, Garcia-Agreda et al. (2011), Sanchirico et al. (2011), and Di Benedetto et al. (2012) presented

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