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Quantifying the effect of strong ignition sources on particle preconditioning and distribution in the 20-L chamber

Chris T. Cloney [a, b, *], Robert C. Ripley [a, b], Paul R. Amyotte [a], Faisal I. Khan [c]

[a] Process Engineering & Applied Science, Dalhousie University, Halifax, NS, Canada
[b] Martec Ltd., Lloyd's Register, Halifax, NS, Canada
[c] Process Engineering, Memorial University, St. John's, NL, Canada

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ABSTRACT

Computational fluid dynamics is used to investigate the preconditioning aspect of overdriving in dust explosion testing. The results show that preconditioning alters both the particle temperature and distribution prior to flame propagation in the 20-L chamber. A parametric study gives the fluid pressure and temperature, and particle temperature and concentration at an assumed flame kernel development time (10 ms) for varying ignitor size and particle diameter. For the 10 kJ ignitor with 50% efficiency, polyethylene particles under 50 μm reach 400 K and may melt prior to flame propagation. Gases from the ignitor detonation displace the dust from the center of the chamber and may increase local particle concentration up to two times the nominal value being tested. These effects have important implications for explosive testing of dusts in the 20-L chamber and comparing to larger 1-m^3 testing, where these effects may be negligible.

1. Introduction

The large energy release from chemical ignitors in dust explosion testing can overdrive the system and alter measured explosion characteristics. Using computational fluid dynamics (CFD), the preconditioning aspect of overdriving is determined, thereby quantifying the fluid properties, particle temperature, and particle distribution prior to flame propagation. The purpose of this work is to investigate the role of ignitor energy strength and particle size on preconditioning, and to provide insight into the effect of preconditioning on standardized testing. This work is motivated by a gap in understanding of overdriving phenomena and discrepancies reported in the literature between explosion parameters at different testing scales.

Several studies spanning decades of work (Cashdollar & Chatrathi, 1992; Di Benedetto, Garcia-Agreda, Russo, & Sanchirico, 2011; Hertzberg, Cashdollar, & Zlochower, 1986; Zhen & Leuckel, 1997) have reported discrepancies due to ignitor overdriving between explosion parameters (P_{max}, K_{St}, *MEC*, and *LOC*) measured in the 20-L and 1-m^3 vessels. Many studies have divided the overdriving phenomena into two categories: preconditioning effects and ignitor induced pressure rise (Cashdollar & Chatrathi, 1992; Going, Chatrathi, & Cashdollar, 2000; Proust, Accorsi, & Dupont, 2007). Preconditioning occurs when the ignition energy changes the initial conditions of the system prior to flame propagation. Ignitor induced pressure rise is caused by the ignitor energy release and particle reaction due to the ignition system which would be absent if flame propagation could be achieved with a negligible energy source.

In an experimental study, the MEC of iron dust, Lycopodium, RoRo93, Pittsburgh coal, and Gilsonite were found to be dependent on ignitor energy in the 20-L vessel (Going et al., 2000). However, only the Pittsburgh coal and Gilsonite showed ignitor size dependency in the 1-m^3 vessel and in general the decrease in MEC due to an increase in ignitor energy was smaller at this testing scale.

In a recent work, Proust et al. (2007) collected and summarized the results of several studies on various dusts, in which substantial discrepancies were found between P_{max} and K_{St} in the two standard testing vessels. Caution should be used when directly comparing these results as it is unclear whether particle size distribution or testing conditions were the same in the two vessels. With this in mind, it appears that preconditioning in the 20-L vessel may preheat the particles enough to change the phenomenology of the reaction during flame propagation. Some dusts that were found to be inexplosible in the 1-m^3 chamber have substantial rates of pressure rise in the 20-L vessel.

An exploration of the combined effect of ignition energy and initial turbulence in the 20-L chamber has recently been conducted

* Corresponding author. Martec Limited, Suite 400, 1888 Brunswick Street, Halifax, Nova Scotia, B3J 3J8, Canada. Tel.: +1 902 425 5101x246.
E-mail address: chris.cloney@dal.ca (C.T. Cloney).

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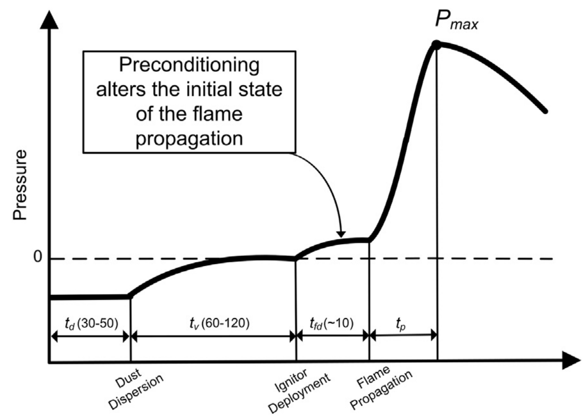

Fig. 1. Schematic of the pressure history and associated timescales (in milliseconds) involved in the 20-L explosion testing process. Preconditioning occurs during the flame kernel development time denoted by t_{fd}.

with dust–air and hybrid gas/dust–air mixtures near the gas lower-flammability-limit conditions (Di Benedetto et al., 2011). These authors define an explosion delay time as the combination of the ignition delay time and maximum rate of pressure rise induction time. For the mixtures tested, it was found that in the 20-L vessel the mass-normalized rate of pressure rise is independent of ignition energy, except for the effect on the explosion delay time and secondary effect on the turbulence in the chamber at the beginning of flame propagation. It may be important to note that comparatively few dust–air results were reported when compared to gas/dust–air and that the ignition energy independence may be isolated to the hybrid testing condition. Hybrid systems are not a main focus in the current work, however preconditioning and overdriving under these conditions should be an area of future study.

Although many aspects of overdriving and preconditioning have been investigated by exploring the effect on explosion parameters, few studies have focused on the actual dynamics of the ignitor energy release and the particle–fluid interaction prior to flame propagation. In the current work, CFD modeling is used to investigate the ignitor energy release and to quantify the gas and particle state prior to flame propagation. Although these results are specific to the individual particles being modeled and the numerical methods used, they will aid in investigating some of the discrepancies found in experimental testing.

The *Chinook* explosion and gas dynamics code (Martec Limited, NS, Canada) is used to model the ignitor energy release and subsequent fluid interaction with polyethylene particles prior to flame propagation. A discussion of the testing and preconditioning process is given followed by a description of the numerical model setup and background theory. The numerical model is used to explore preconditioning dynamics in the 20-L and 1-m^3 vessels, including non-equilibrium particle heating during the flame kernel development, acceleration of the particles from the center of the chamber, interaction with the expanding gaseous ignition products, and interaction with the shock from the assumed prompt energy release of the ignitor. A parametric study shows the effect of ignitor size and particle diameter on the quasi-static fluid temperature and pressure, and particle temperature and concentration in the 20-L vessel at an assumed flame kernel development time (10 ms).

2. Background

The steps in the explosion testing process are discussed with respect to overdriving and preconditioning phenomena are explored. A description of the one-dimensional (1D) spherical model used to investigate preconditioning is given along with the theory and assumptions involved.

2.1. Explosion testing process

The typical explosion testing process involves pneumatic dispersion of the dust, ignitor detonation after a delay time, flame kernel development, and flame propagation. A schematic detailing a typical pressure history is given in Fig. 1. The timescales shown in the figure are adapted from Di Benedetto et al. (2011) for the 20-L chamber and include time delay of the outlet valve (t_d), ignition delay time (t_v), time from ignitor deployment to flame propagation (defined here as flame kernel development time, t_{fd}), and flame propagation time (t_p). Similar steps with longer time-scales occur in the 1-m^3 chamber as described by Proust et al. (2007). The goal in the current work is to investigate preconditioning of the fluid–particulate system during flame kernel development, and to attempt to quantify changes from the nominal testing state prior to flame propagation.

Preconditioning is a complex process dependent on many variables including ignitor strength, particle diameter, and particle thermophysical properties. A schematic showing the ignitor deployment process for an idealized spherical ignitor located at the center of the vessel is shown in Fig. 2. If the ignitor reaction is assumed instantaneous the expansion of gaseous ignition products drives a shock wave through the testing vessel. As the shock passes through the particles they are accelerated outward and heated.

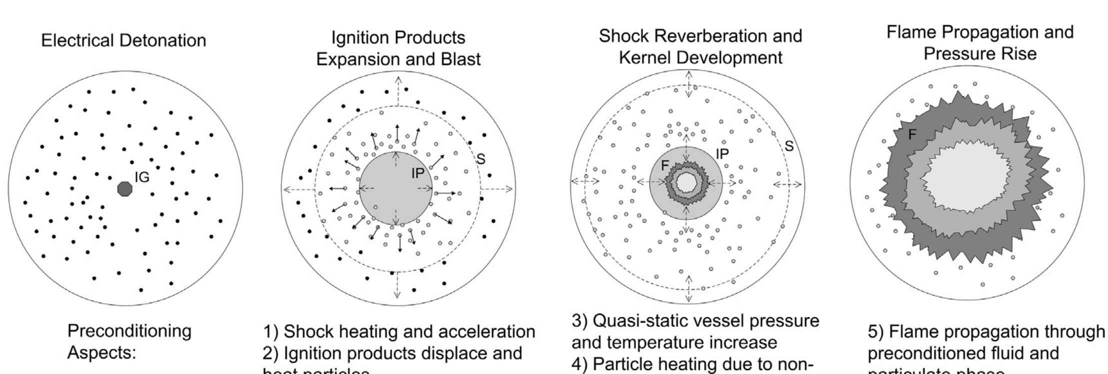

Fig. 2. Schematic showing idealized ignitor detonation process and flame kernel development. The ignitor (IG), shock wave (S), gaseous ignition products (IP), and fireball (F) are denoted.