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Experimental and numerical investigation of constant volume dust and gas explosions in a 3.6-m flame acceleration tube

Trygve Skjold [a], [b], [*], Diana Castellanos [c], [d], Kjetil L. Olsen [a], [b], Rolf K. Eckhoff [b]

[a] GexCon AS, Bergen, Norway
[b] University of Bergen, Bergen, Norway
[c] Mary Kay O'Connor Process Safety Center, TX, USA
[d] Texas A&M University, College Station, TX, USA

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ABSTRACT

This paper describes an experimental investigation of turbulent flame propagation in propane-air mixtures, and in mechanical suspensions of maize starch dispersed in air, in a closed vessel of length 3.6 m and internal cross-section 0.27 m × 0.27 m. The primary motivation for the work is to gain improved understanding of turbulent flame propagation in dust clouds, with a view to develop improved models and methods for assessing explosion risks in the process and mining industries. The study includes computational fluid dynamics (CFD) simulations with FLACS and DESC, for gas and dust explosions respectively. For initially quiescent propane-air mixtures, FLACS over-predicts the rate of combustion for fuel-lean mixtures, and under-predicts for fuel-rich mixtures. The simulations tend to be in better agreement with the experimental results for initially turbulent gaseous mixtures. The experimental results for maize starch vary significantly between repeated tests, but the subset of tests that yields the highest explosion pressures are in reasonable agreement with CFD simulations with DESC.

1. Introduction

Dust explosions pose a hazard whenever combustible material is present as fine powder, the powder can be dispersed in air to form an explosible dust-air cloud within a sufficiently confined and/or congested volume, and there is an ignition source present. Although the technology for preventing and mitigating dust explosions has progressed considerably, recurring accidents in the process and mining industries demonstrate the need for improved knowledge in this area (Amyotte, 2013; Eckhoff, 2003). Flame propagation in dust clouds is a complex phenomenon, and detailed modelling from first principles is not straightforward. Most methods for estimating the consequences of industrial dust explosions rely on empirical correlations, and the explosion parameters for a specific dust sample are typically determined in standardized tests in constant volume explosion vessels. The process of generating mechanical suspensions in closed vessels entails transient turbulent flow conditions, where the root-mean-square of the turbulent velocity fluctuations u'_{rms} and the spectrum of turbulent length scales ℓ vary significantly during dispersion and combustion (Dahoe, 2000; Dahoe, Cant, Pegg, & Scarlett, 2001; Dahoe, Cant, & Scarlett, 2001; Dahoe, van der Nat, Braithwaite,& Scarlett, 2001; Pu, 1988; Pu, Jarosinski, Johnson, & Kauffman, 1990; Pu, Jarosinski, Tai, Kauffman, & Sichel, 1988; Skjold, 2003). This complicates the task of estimating fundamental combustion parameters, such as the laminar burning velocity S_L and the laminar flame thickness δ_L, for dust clouds (Amyotte, Chippett, & Pegg, 1989; Dahoe, 2000; Dahoe et al., 2013; Dahoe, Zevenbergen, Lemkowitz, & Scarlett, 1996; Dyduch & Skjold, 2010; Kalejaiye, Amyotte, Pegg, & Cashdollar, 2010; Lee, Pu, & Knystautas, 1987; Lee, Zhang, & Knystautas, 1992; Pekalski, 2004; Skjold, 2003, 2007; 2014a; van der Wel, 1993; van der Wel, van Veen, Lemkowitz, Scarlett, & van Wingerden, 1992).

The primary motivation for the present work has been to gain better understanding of flame propagation in dust clouds by exploring similarities and differences between turbulent gas and dust flames under similar experimental conditions, with a view to develop improved models and methods for assessing and reducing the risk posed by dust explosions in industry. The comparison of flame propagation in gaseous mixtures and suspensions of fine particles has direct relevance for the modelling in the computational fluid dynamics (CFD) codes FLACS (GexCon, 2014) and DESC

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[*] Corresponding author. GexCon AS, Bergen, Norway. Tel.: +47 488 67 968.
E-mail address: trygve@gexcon.com (T. Skjold).

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(Skjold, 2007). Bond, Knystautas, and Lee (1986) demonstrated that the effect of turbulence on flame propagation is similar for clouds of maize starch and mixtures of 7.5% methane in air. Abdel-Gayed, Bradley, and Lawes (1987) used dimensionless parameters to correlate 1650 separate measurements of turbulent burning velocity S_T for various gaseous fuels. Bradley, Chen, and Swithenbank (1988) measured S_T in mechanical suspensions of maize starch particles dispersed in air and found similar correlations between S_T/S_L, u'_{rms}/S_L and the Karlovitz stretch factor K as for gaseous fuel/air mixture ($K = (u'_{\mathrm{rms}}/l_\lambda)(\delta_L/S_L)$, where ℓ_λ is the Taylor microscale and δ_L is the laminar flame thickness). Bray (1990) expressed the data from Abdel-Gayed et al. by an empirical expression, and this correlation forms the basis for the burning velocity model in the CFD codes FLACS (Arntzen, 1998) and DESC (Dust Explosion Simulation Code, or FLACS-DustEx). It is not obvious that an empirical correlation derived from experiments with gaseous fuel-air mixtures can be used for estimating S_T in dust clouds, i.e. for *'premixed combustion with non-premixed substructures'* (Williams, 1996). In principle, the modelling approach in DESC only applies to clouds of fine dusts with high volatile content, where flame propagation is driven principally by gas phase reactions (Bradley et al., 1988). Previous validation work indicate that DESC can simulate the course of dust explosions in complex geometries with reasonable accuracy for fuels such as maize starch and coal dust (Castellanos, Skjold, van Wingerden, Eckhoff, & Mannan, 2013; Skjold, 2007, 2010, 2014b; Skjold, Arntzen, Hansen, Storvik, & Eckhoff, 2006; Skjold et al., 2005a,b; Tascón, Ruiz, & Aguado, 2011). Lee et al. (1987) emphasized that the concept of burning velocity requires the existence of a well-defined flame zone. Unfortunately, it is not straightforward to specify unambiguous criteria for the applicability of the modelling approach in DESC, for instance based on particle size distribution, the fraction of volatile components in the fuel, spatial scale, etc. In order to account for the inherent differences between combustion in gaseous fuel-air mixtures and dust-air suspensions, there is a need for further validation and improved modelling of multiphase flow and heterogeneous combustion in DESC.

This paper describes an experimental study of turbulent flame propagation in a 3.6 m long flame acceleration tube (FAT) with internal cross-section 0.27 m × 0.27 m (i.e. 262 l), for two types of fuel: propane-air mixtures and mechanical suspensions of maize starch dispersed in air. The experimental approach is similar to that of Pu, who used a 1.86 m long tube with diameter 0.19 m (i.e. 53 l) to investigate the influence of obstacles on flame propagation in clouds of maize starch and lean methane-air mixtures (Pu, 1988; Pu, Mazurkiewicz, Jarosinski, & Kauffman, 1988). Skjold et al. (2005b) simulated these experiments with DESC 1.0b2. The apparatus constructed for the present work is twice the length and almost five times the volume, with quadratic cross section, and oriented horizontally rather than vertically. The increase in scale reduces the influence of radiative heat losses somewhat, and it is straightforward to implement a geometry model on the Cartesian computational grid used in FLACS and DESC. The FAT is equipped with a modern data acquisition system and windows distributed along the entire length of the vessel. This facilitates visual observations of flame propagation, that combined with simultaneous pressure measurements might reveal fundamental differences between gases and dusts with respect to flame thickness or degree of volumetric combustion. Previous studies in the FAT focused on developing reliable and robust methods for detecting time of flame arrival in turbulent dust flames (Enstad, 2009; Kalvatn, 2009; Olsen, 2012; Skjold, Kalvatn, Enstad, & Eckhoff, 2009).

2. Experiments

Figs. 1 and 2 show the flame acceleration tube. The main apparatus consists of three sections, each 1.2 m in length and with internal dimensions 0.27 m × 0.27 m, connected by flanges. The first section is fixed to the foundation, whereas the two others are fitted with wheels and can move along rails when the flanges are disconnected. Each section is fitted with a separate dispersion system, cable trays for power supply and signal cables, flame probes, windows for visual flame tracking, flexible lines for gaseous fuel and compressed air, and brackets for fixing additional obstacles. The dispersion nozzles, brackets and probes represent inherent obstacles.

Table 1 summarizes the experiments. In all tests, a vacuum pump is used to evacuate the vessel, and the pressure is adjusted to 0.60 bar*a* prior to injection of air from the pressurized reservoirs (3 × 2.0 l, 17.2 bar*a*). The amount of propane added to the vessel is controlled by monitoring the pressure, and weighted dust samples are placed in the pre-dispersion chambers (3 × 0.90 l). For tests under initially turbulent conditions, the ignition source, either weak sparks discharges or chemical igniters, are triggered 1.0 s after onset of dispersion. Testing of propane under initially quiescent conditions follow the same procedure, but with ignition triggered several minutes after completing the injection process. Fig. 2 shows the position of the ignition source (Ign.).

The maize starch, of type Meritena A (Eckhoff, Fuhre, & Pedersen, 1987), was dried prior to testing. The 10, 50 and 90 percentiles of the particle size distribution are 6, 13 and 20 μm, respectively (Skjold et al., 2006). Some experiments with dust included additional obstacles in the tube, either 10 or 20, equally spaced throughout the last three metres of flame propagation (i.e. 0.30 or 0.15 m obstacle spacing). The obstacles had a blockage ratio of 0.42. Explosion experiments with additional obstacles and gaseous mixtures proved too violent for both the apparatus and the measurement system, even for lean mixtures of 3.0% propane in air (Olsen, 2012).

The sampling frequency of the data acquisition system (National Instruments USB-6259 BNC M Series) was 50 kHz. Fig. 2 illustrates the pressure sensors (P1–P3) and flame probes (T1–T3) on the three sections of the tube. Piezoelectric pressure transducers (Kistler 701A) and charge amplifiers (Kistler 5011) measured the pressure development in the reservoirs and inside the tube. Flame

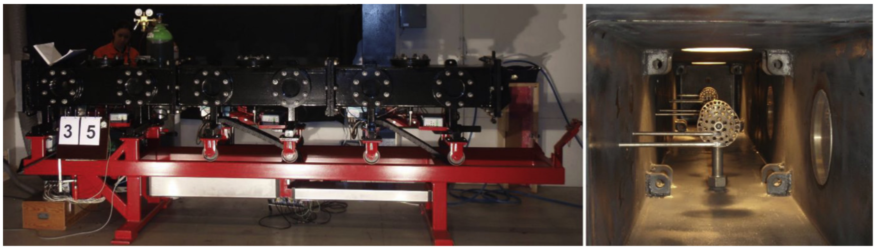

Fig. 1. The 3.6-m flame acceleration tube (left) and its internal geometry (right).