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Effect of scale on freely propagating flames in aluminum dust clouds

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ABSTRACT

The majority of experimental tests done on combustible dusts are performed in constant volume vessels that have limited or no optical access. Over the years, McGill University has been developing alternative experimental techniques based on direct observation of dust flames, yielding reliable fundamental parameters such as flame burning velocity, temperature and structure. The present work describes two new experimental set-ups allowing direct observation of isobaric and freely propagating dust flames at two sufficiently different scales to test the influence of scale on dust flame phenomena. In the laboratory-scale experiments, a few grams of aluminum powder are dispersed in transparent, 30 cm diameter latex balloons that allow for full visualization of the spherical flame propagation. In the field experiments, about 1 kg of aluminum powder is dispersed by a short pulse of air, forming a conical dust cloud with a total volume of about 5 m^3. High-speed digital imaging is used to record the particle dispersal and flame propagation in both configurations. In the small-scale laboratory tests, the measured flame speed is found to be about 2.0 ± 0.2 m/s in fuel-rich aluminium clouds. The burning velocity, calculated by dividing the measured flame speed by the expansion factor deduced from thermodynamic equilibrium calculations, correlates well with the previously measured burning velocity of about 22–24 cm/s from Bunsen dust flames. Flame speeds observed in field experiments with large-scale clouds, however, are found to be much higher, in the range of 12 ± 2 m/s. Estimations are presented that show that the presumably greater role of radiative heat transfer in larger-scale aluminium flames is insufficient to explain the six-fold increase in flame speed. The role of residual large-eddy turbulence, as well as the frozen-turbulence effect leading to large-scale dust concentration fluctuations that cause flame folding, are discussed as two possible sources for the greater flame speed.

1. Introduction

The ever increasing role of modern technologies based on metal powders, such as powder metallurgy, chemical processing, plasma spraying, etc., and the rapidly increasing scale of metal powder production are overshadowed by the increased human and material cost of accidents caused by metal dust explosions (Cashdollar and Hertzberg, 1987). In spite of the strong impetus to implement state-of-the-art preventive measures to mitigate accidents, the progress in this field has been relatively slow in comparison to other branches of preventive science. The slow progress in prevention of metal dust explosions reflects the relatively underdeveloped state of combustion science in this field in contrast to the impressive progress achieved in understanding the physics and chemistry of homogeneous gas flames.

The primary reason for the slow progress in dust combustion science is rooted in the difficulties of extracting the fundamental combustion parameters, such as ignition temperature, burning velocity, flame quenching distance and flame structure, from laboratory experiments with metal dust clouds. Traditionally, most dust combustion tests are performed in constant volume vessels. Though convenient for empirical testing, constant-volume bombs have limited or no optical access, and the pressure rise is the only parameter typically measured in most experiments. The pressure history provides limited insight into the dust flame propagation since the deduction of the flame speed from the rate of pressure rise is neither accurate nor representative if the flame propagation deviates from the ideal picture of a spherically symmetric laminar flame (Hertzberg et al., 1988; Pu et al., 2007). Some experiments have demonstrated that the residual turbulence induced in the

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mixture during the dust dispersal phase may have a considerable influence on flames ignited with short delay times after dispersal (Dahoe et al., 2001; Kang Pu et al., 1989). Furthermore, the implementation of modern flame diagnostic techniques, such as emission and laser-absorption spectroscopy, is required to elucidate the flame structure and verify equilibrium calculations of flame temperatures against experimental values, which is difficult to accomplish in constant volume bombs.

An array of experimental set-ups allowing for visual observation of flames in dust and hybrid combustible gas-dust clouds has been developed at McGill University over the past two decades. They are based on experimental methods that have proven to be successful in gas flame research and include Bunsen dust burners (Goroshin et al., 1996a; Goroshin et al., 2007; Julien et al., 2014a, b; Soo et al., 2013), counter-flow dust burners (under development), as well as dust flames propagating in transparent tubes and narrow channels (Palecka et al., 2014; Tang et al., 2009). These set ups have permitted an accurate measurement of the burning velocities (Goroshin et al., 1996a), flame quenching distances (Goroshin et al., 1996b) and spectroscopic diagnostics of the dust flame structure (Goroshin et al., 2007) in dust and hybrid combustible gas-dust mixtures (Julien et al., 2014a, b). A large series of dust combustion experiments were performed at low gravity on board a parabolic flight aircraft (Goroshin et al., 2011; Tang et al., 2011; Tang et al., 2009). By eliminating particle sedimentation and natural convection, microgravity conditions have permitted the observation of laminar dust flames for a very wide range of particle sizes. The current paper presents two new experimental systems developed to investigate the effects of scale on the flame propagation in combustible dust clouds. The first apparatus, which is similar to the one recently reported by Skjold et al. (2013), allows the laboratory observation of isobaric spherical flames in dust clouds dispersed in transparent latex balloons with an initial volume of about 14 L. The second apparatus permits the creation of unconfined dust clouds with a total volume in the range of 5–10 m^3.

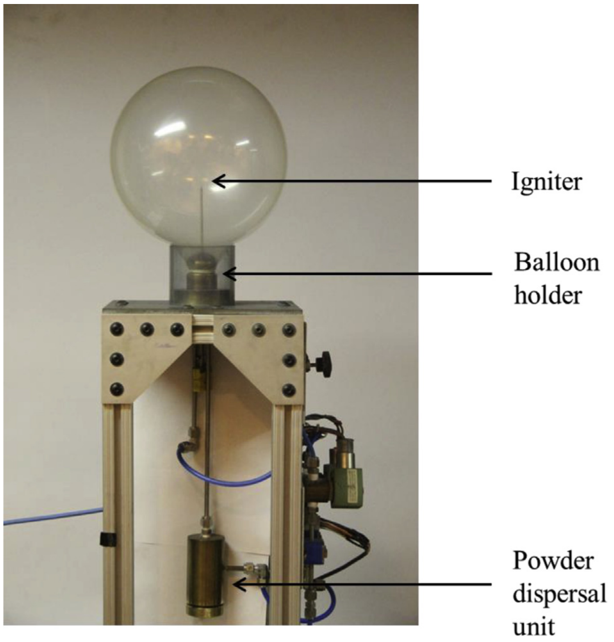

Fig. 1. Apparatus for small-scale flames.

2. Experimental methods and results

2.1. Small-scale spherical dust flames in transparent latex balloons

Fig. 1 shows a photograph of the experimental apparatus, including the dispersion and ignition systems (the control unit, mixing tank and safety housing are not visible). The balloon is placed on the neck of the balloon holder, which has three different ports: one for inflating the balloon, one for dispersing the powder and one for the igniter. At the start of a test, the balloon is inflated through a solenoid valve controlled by a remote timer. Once the balloon reaches the desired size, about 30 cm in diameter, a calibration image is taken. The powder, placed in a receptacle within the dispersion unit, is then injected into the balloon. The injection is initiated by the opening of a second solenoid valve, causing a high-pressure gas jet to impinge on the powder surface, lofting the powder, and entraining it into the flow through a perforated cap and into the balloon. This method results in a uniform dispersion of the powder throughout the balloon. The two-phase flow is initially turbulent, with prominent, large-scale vortices moving primary along the wall of the balloon. A delay is applied to allow the turbulence to decay before igniting the mixture by discharging a capacitor through a 100 micron thick tungsten wire positioned at the center of the balloon. A small, yet unavoidable, amount of powder is deposited on the surface of the balloon during the powder dispersal process, making the effective concentration somewhat lower than the one calculated based on the initial powder mass and the volume of the inflated balloon. It is estimated that the amount of deposited powder does not exceed 10% of the initial powder weight in the receptacle.

The transparent balloon allows for the imaging of all experimental stages with a high-speed camera, including powder dispersal, ignition, and the subsequent isobaric flame propagation. The dust dispersal process, with the balloon uniformly backlit with a diffuse light source, is recorded at 300 frames per second using a Photron SA5 camera. The flame propagation process is recorded with the same camera typically at 5000 frames per second.

This method of measuring flame speed is first validated using methane-air mixtures of various equivalence ratios. The contour of the flame on the high-speed movie is traced for every frame and the radius is taken to be the average distance between the contour and the center-of-mass. The flame speed is equal to the slope of the curve, which is found by linear regression. Conservation of mass

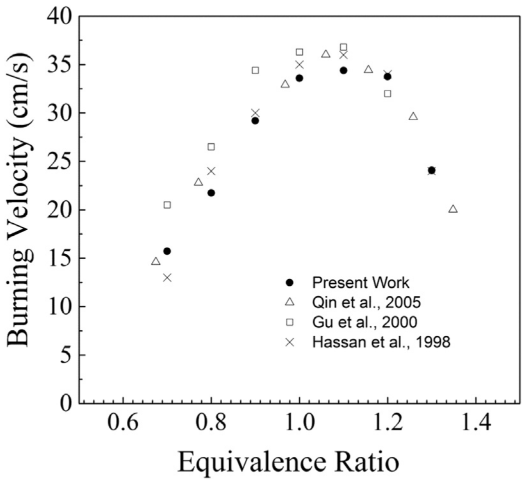

Fig. 2. Burning velocity vs. equivalence ratio for methane-air mixtures compared to results from other freely-propagating spherical flames.