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Determination of the burning velocity of gas/dust hybrid mixtures

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ABSTRACT

The laminar flame speed is an essential input for Computational Fluid Dynamics simulation programs aiming to predict the effects of explosions. In this study, an approach to assess fundamental flame propagation properties from the analysis of the flame velocity as a function of its stretching and hydrodynamic instabilities was developed. A numerical tool was developed to analyse videos of propagating flames in order to estimate their unstretched burning velocities.

Markstein's theory, developed for gases and assuming a linear relation between the flame stretch and its speed, was then extended to dust clouds and hybrid mixtures of starch and methane. At first, the approach was validated with pure methane and was extended to pure starch and hybrid mixtures of both compounds.

Finally, it appears that hybrid mixtures, especially when the gas concentration is greater than the lower explosive limit, can present a synergetic effect enabling faster flame propagation with regard to pure gas flames. Indeed, the stretching of a gas flame is strongly influenced by the addition of dusts. Nevertheless, for lower gas concentrations and larger dust concentrations called 'dust-driven regime', the presence of powders tends to limit the flame velocity to that of the less reactive compound, i.e. the dust.

1. Introduction

Predicting the flame propagation during a dust explosion in complex geometries is still a challenge that mobilizes numerous technical, computational and human resources. A perfect knowledge of dust explosion mechanisms would be necessary to propose a fully predictive approach. But it should be carried out by taking into account the specific properties of each combustible powder, which is time consuming if not illusory. Another approach consists of determining experimentally the inherent characteristics of dust–air mixtures (such as the laminar flame speed) and using them as an input for Computational Fluid Dynamics simulation programs. However, if the experimental characterization of the burning rates of gases from the speed of their flame front is still challenging, when dealing with turbulent dust–air suspensions, it is considered as: "one of the most complicated combustion process to be studied" (Skjold, 2003).

Such goal has been pursued for many years, starting with the characterization of the burning velocity of gas/air mixtures. The first rough estimation of a burning rate was performed by Davy in 1816 on a methane flame (Davy, 1816). Afterwards, experimental approaches such as the burner method and the tube method were developed by scientists such as Bunsen or Mallard and Le Chatelier (Glassman and Yetter, 2008). The measurement principles of the flame speed were mainly based on the quantification of the volume flow rate of the gas–air mixture. The influence of the flame surface and hence, of flame stretching was first studied by Gouy in 1879 (Taylor, 1991). It was only 50 years later that a new approach was proposed by Stevens: the contained explosion method (Stevens, 1926). Nowadays, these three methods for measuring the laminar burning velocity of fuel–air mixtures are still used and have been also implemented for dust–air flames: the burner method (Cassel, 1964; Dahoe et al., 2002; Goroshin et al., 1996), the contained explosion method (Huéscar Medina et al., 2015; Skjold, 2003; Van Der Wel, 1993) or tube method (Proust and Veyssiere, 1988; Proust, 2006; Schneider, 2006; Schneider and Proust, 2007; Wang et al., 2006). Few works have been also devoted to the study of the flame propagation of hybrid mixtures. Bradley et al. (1989, 1994) studied the laminar burning velocities of methane–air–graphite mixtures and of fine coal

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dusts by using a burner. They notably underlined that the presence of the powder does not change the gas phase composition and kinetics during the combustion step. Liu et al. (2007) and Chen et al. (2008) studied the flame propagation of coal dust–methane mixtures in a vertical combustion vessel to measure the flame speed. They observed that the presence of methane, even at concentrations lower than the lower explosive limit (LEL), increases the flame speed and the flame front temperature. They also showed some kind of decoupling between gas and dust combustion: in a first step, a feeble light due to methane combustion, was observed and only subsequently the coal dust starts participating.

Despite the numerous studies that have already been carried out, the large scatter in the experimental data collected by using the previously mentioned methods shows that determining the burning velocity of dust–air mixtures from the observation of flame front propagation is a challenging enterprise. Indeed, such issues are notably due to the variability of powders properties (particle size distribution, moisture...), the physical impossibility to generate a quiescent dust cloud, and the impact of powder on the flame radiation. The latter consideration can probably be neglected when dealing with small organic particles for which the rate-limiting mechanism is generally the combustion of volatiles. Nevertheless, it is not the case for metal particles. Moreover, for Nusselt flames, i.e. when the combustion is limited by the oxygen diffusion at the surface of the particles (heterogeneous combustion such as for graphite or refractory metals), the persistence of solid fuels ahead of the flame is not negligible and the flame deformation due to their presence should be considered.

As a consequence, the goal of this study is to develop an approach to assess fundamental flame propagation properties, not only from closed vessel experiments and pressure–time evolution curves, but from the analysis of the flame velocity as a function of its stretching and hydrodynamic instabilities. In a first step, the turbulence of the initial dust cloud and its potential effect on powder ignition has been studied (Cuervo, 2015). In order to validate the approach and the experimental results, the flame propagation of hybrid mixtures of starch and methane was analysed. Furthermore, tests were conducted in standardized apparatuses such as the 20 L sphere (Cuervo, 2015) and data concerning their burning velocities are available in the literature. Besides proposing a new tool to estimate the laminar burning velocity from open tube experiments, the influence of gas addition on dust explosion severity is discussed.

2. Experimental setups and fuels choice

2.1. Flame propagation setup

Dufaud et al. (2012) previously started to develop a technique that allows to estimate the fundamental flame speed of gases, dusts and their hybrid mixtures (Di Benedetto et al., 2011). In the present work, the technique was standardised to reduce the variations in the experimental conditions. A modified Hartmann tube (Mike 3) was connected to a 7 × 7 × 100 cm tube capable of withstanding low pressure explosions (Fig. 1). The tube has two opposite walls made of glass and the two others made of stainless steel. The top end was equipped with a removable vent, which opens at 1.15 atm, whereas the bottom end was closed with a dispersion cup of hemispherical shape, where the dust was initially placed. A 0.6 L cylinder allowed to premix air with a combustible gas before introducing it inside the tube. The pressure in the tube was vacuumed to 15 mbar and then the premixed gas was introduced through the injection line. After a first gas injection, air was introduced to set the internal pressure at 0.7 bar. Then, in order to generate an homogeneous cloud, the dust was dispersed into the chamber by an gas/air blast of 7 bars issuing from the mushroom-shaped nozzle connected to the 0.6 L cylinder. As a consequence, before ignition, the initial pressure in the tube is 1.0 bar.

The tests were carried out with ignition energies from 10 to 1000 mJ to avoid 'overdriving' phenomena (Cashdollar, 2000). The delay between the dust dispersion and its ignition is called t_v. This parameter was adjustable between 30 to 300 ms, but was set at 120 or 180 ms for this study.

The flame propagation process was recorded by a high speed video camera (Phantom V91) with a frame rate up to 4000 fps. The timing sequences and the ignition system were controlled remotely by means of an electronic system adapted from the modified Hartmann tube.

In this work a digital tool was developed to automatize the analysis of the videos; this method will be discussed in Section 3.

2.2. Choice of hybrid mixtures

In this study, five kinds of mixtures of starch and methane were chosen to compare the way their flames propagate. The particle-size distribution of starch powders was determined in isopropanol by a laser diffraction analyser (Mastersizer, Malvern Instrument). The characteristic diameters of the volumetric distribution, d_{10}, d_{50} and d_{90} were 16, 35 and 76 μm, respectively. These measurements were confirmed by SEM observations. They show that the wheat starch sample is mainly composed of regular particles of spherical or ovoid shapes.

The flammability and explosion properties of pure starch and methane are presented in Table 1. The minimum ignition energy (MIE) was measured in the modified Hartmann tube, while the Lower Explosive Limit (LEL) of the gases, the Minimum Explosive Concentration (MEC) of the dusts, the maximum explosion pressure P_{max} and maximum rate of pressure rise $\left(\frac{dP}{dt}\right)_{max}$ were measured in the 20 L explosion sphere with 100 J igniters and a 60 ms ignition delay (turbulent conditions).

Each of the five mixtures corresponds to a specific hybrid mixture regime described by Garcia-Agreda et al. (2011) and Sanchirico et al. (2011): gas-driven, dust-driven, dual driven or pure fuel (gas or dust). LEL_g, UEL_g and MEC_d correspond to the lower and upper explosivity limits of methane and to the minimum explosive concentration of starch, respectively. If C_{dust} or C_d is the dust concentration and y_g the flammable gas concentration, the limits of these regimes are given by the ratios defined by C_d/MEC and y_g/LEL. A dust driven explosion will be obtained if C_d/MEC is greater than unity and y_g/LEL is lower than 1, whereas a gas driven explosion will be obtained for $C_d/MEC < 1$ and $y_g/LEL > 1$. A dual-fuel explosion is expected if both ratios are greater than unity. The mixture for each regime was chosen for being the one with the highest maximum rate of pressure rise found during explosion tests performed in the standard 20 L sphere (Cuervo, 2015). It should be stressed that, in a semi-confined vessel, the dust concentration C_d has to be estimated from the volume occupied by the dispersed dust and not from the total volume of the vessel. Hence, various dust dispersion tests were performed using a high-speed video camera in order to assess the maximum dispersion height of the powder. An average value of 25 cm was obtained and used to calculate C_d. The mixture compositions are listed in Table 2 as well as the adiabatic temperatures at constant pressure ($T_{ad}|_P$) estimated with the CEA software (Gordon and McBride, 1994). It should be noticed that the adiabatic flame temperature of pure methane is in good