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Experimental Determination of Aluminum Burning Velocity During Flame Propagation in a Tube

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Modeling the consequences of dust explosions is a challenging research topic. A key parameter of these models is the burning velocity, which represents the consumption rate of the reactants by the flame front. Especially, a relation between burning velocity and RMS (root-mean square) air velocity fluctuations has to be implemented in such models; RMS velocity fluctuations representing the turbulence of the fresh air flow in front of the flame front.This paper focuses on the experimental determination of this relation in the case of dust flames propagating in a tube. The most commonly used method is the "open-tube method", which assumes a constant thermal expansion coefficient and the estimation of a 3D flame surface. These assumptions are discussed, and a new method is proposed, based on the measurement of the fresh flow velocity in front of the flame front. The corresponding optical setup implemented for analyzing aluminum burning velocity is then exposed. Analysis method for obtaining burning velocity and RMS velocity fluctuations is detailed. Finally, first results obtained are presented and commented.

1. Introduction

Dust explosion is a major concern in industries dealing with powders and dusts. The mechanisms of flame propagation during such explosion are not well understood, especially for metallic dusts. Most studies aim to characterize the sensitivity and severity parameters, using standardized setups like the Hartmann Tube or the 20L-sphere (Dufaud et al., 2012). Even if these parameters are useful for risk analysis in the industry, they are not sufficient to model accurately the consequences of accidents in real conditions. To model accurately the consequences, numerical simulations are needed. Most of the current models used for dust explosions are based on models designed for gas explosions. One key parameter of these models is the burning velocity (S_u), which represents the consumption rate of the reactants. This burning velocity depends on the characteristics of the turbulence of the flow. For this purpose, a key point for numerical simulations is the determination of the relationship between the burning velocity and the RMS velocity fluctuations (V_{RMS}) (Russo and Di Benedetto, 2007).

This relationship can be obtained from the analysis of stabilized flames (Goroshin et al., 1996b; Julien et al., 2017). However, for simulating real accidents, mechanisms involved during flame propagation have to be understood. For this purpose, this relationship has also to be determined from propagating flames. Burning velocity can be determined from experiments realized inside the 20-L standardized explosion sphere; for example, from the evolution of the pressure during the flame propagation (Dahoe and de Goey, 2003). However, because of the lack of optical accesses, flame propagation mechanisms cannot be analyzed from these experiments. Tubes with optical accesses are used to visualize and analyze the flame propagation processes. Especially from the visualization of the propagating flame, the turbulent burning velocity can be deduced (Di Benedetto et al., 2011). The mostly used method is the "open-tube method".

This study proposes an alternative method for estimating this turbulent burning velocity, but also for analyzing the influence of RMS velocity fluctuations on this turbulent burning velocity. Indeed, in the first part of this paper, the "open-tube method" is presented. Some limitations of this method are highlighted, especially for the case of aluminum dusts. Then another method, the "direct method", is proposed. Finally, first results obtained are presented and analyzed.

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2. Limitations of the open-tube method

2.1 Presentation of the open-tube method

The “open-tube method” has already been presented more in details in a previous paper (Chanut et al., 2018). This method is used to determine the burning velocity from the visualization of the propagation of a flame in a tube. Indeed, with the images obtained by direct visualization, the evolution of the position of the flame front is obtained. The deduced propagation velocity (V_p) represents the flame speed in the laboratory referential; this velocity depends among other on the geometry of the apparatus. This propagation velocity is different from the turbulent burning velocity (S_u) which represents the consumption rate of the reactants by the flame front. With the “open-tube method”, this turbulent burning velocity is deduced from the propagation velocity following two main steps. First, as the flame propagates from the bottom closed end of a tube to the open top end, thermal expansion of the burned gases has to be taken into account. Indeed, these burned gases push the flame front to the top; thus, the propagation velocity is higher than the burning velocity. A first burning velocity (S_{u1}) is deduced from the propagation velocity (V_p), where χ is the thermal expansion coefficient:

$$S_{u1} = \frac{V_p}{\chi} \tag{1}$$

$$\chi = \frac{\rho_u}{\rho_b} \approx \frac{T_b}{T_u} \tag{2}$$

Where ρ_u and ρ_b are the densities of the unburned and burned gases respectively, T_u and T_b are respectively the temperature of the unburned gases (ambient temperature) and of the flame temperature (supposed adiabatic). It has to be noticed that solid aluminum particles combustion will not participate to volume expansion by solid to vapor change since reaction product is aluminum oxide (alumina) which will be recovered in condensate state (flame temperature: 3500K (Bucher et al. 1996)). Oxygen consumption reduces volume expansion but is neglected in Eq (1).

The second correction takes into account the shape of the flame front. Indeed, burning velocity is defined for planar flames. However, planar flames are unstable and will not occur in experiments. Thus, the actual flame shape will increase the burning surface, and the volume expansion. The final burning velocity (S_u) is deduced from the previous one (S_{u1}) with the following relation:

$$S_u = S_{u1} \cdot \frac{A'}{A_f} \tag{3}$$

Where A′ is the projected flame area on a horizontal plane (corresponding to a virtual planar flame) and Af is the actual flame surface.

2.2 Limitations of this method

With this method, burning velocity can be estimated from the visualization of the flame front propagation; from these images, the flame position and the flame surface have to be extracted. An important point for this analysis is the quality of these flame images. Indeed, as flames are very luminous, especially in the case of metallic dusts, lots of images exposed in the literature are saturated. However, analysis with saturated images can lead for example to over-estimating the burning velocity with the previous method, as previously discussed (Chanut et al., 2018). In addition to some biases coming from the images quality, some inherent limitations of these methods also exist, as precised above.

2.2.1 Limitations for estimating the turbulent burning velocity

The first step of the method consists on taking into account the thermal expansion of the burned gases. For this purpose, burned gases temperature is supposed to be equal to the adiabatic flame temperature. However, because of heat losses at the tube walls, the real burned gases temperature is less important than the adiabatic flame temperature and will cool with time. For this purpose, the turbulent burning velocity is here under-estimated. This flame temperature is used to calculate the thermal expansion coefficient. This latter is considered as constant during all the flame propagation, but in the case of aluminum dust flames, a pulsating behavior, in terms of light intensity, is observed during the flame propagation (Julien et al., 2015). Thus, this coefficient should vary with these variations of light intensity.

The second step of the method consists on taking into account the flame surface area. However, especially for turbulent flames, this estimation of the 3D flame surface area from 2D images of the flame front is tricky. In most of the cases, the flame front is approximated by a parabolic shape in the plane orthogonal to the images obtained (Khalili, 2012). With this surface approximation, the flame surface area is in general under-estimated and thus the burning velocity is over-estimated. In a previous study, images were obtained in two orthogonal planes. From these two points of view, results of burning velocity were compared. A difference of around 10% was observed (Chanut, 2018). In any case, the error made from this approximation with parabolas is difficult to quantify, especially in the case of turbulent flames.

2.2.2 Limitations for evaluating the influence of RMS velocity fluctuations

As mentioned in introduction, the turbulence level of the flow is expected to influence this turbulent burning velocity. Thus, for each measurement of the turbulent burning velocity, the RMS velocity fluctuations of the flow should be determined and specified. With this “open-tube method”, with only images of flame propagation, the RMS velocity fluctuations of the flow cannot be determined. Several authors focused on the influence of dispersion-induced turbulence on the burning velocity (Dufaud et al., 2012; Proust, 2017). This dispersion-induced turbulence, also named initial turbulence, represents the level of turbulence due to the dispersion of the dust in the tube at the moment of ignition. However, the important data is the turbulence level just ahead the flame front while the flame is propagating in the tube. Indeed, the propagation of the flame in the tube will increase this turbulence level; thus the burning velocity should increase (Eckhoff, 1992). This increase of turbulence by the flame front propagation is in general called the explosion-induced turbulence.

3. Principle of an alternative method: the direct method

An alternative method is proposed to determine the turbulent burning velocity, but also to estimate the turbulence level just ahead the flame front. This alternative method will be called the “direct method”. The principle of this method has been previously proposed by Proust (2006). With this method, the determination of the burning velocity (S_u) is based on the measurement of two other velocities: the flame propagation velocity (V_p, as previously introduced) and the flow velocity ahead the flame front (U). The following relation is used to deduce the burning velocity, with $\vec{n}$ the normal vector to the flame front:

$$S_u = \overrightarrow{V_p}.\vec{n} - \vec{U}.\vec{n} \tag{5}$$

This method is here adapted and applied with an alternative optical technique, as described hereafter. Furthermore, a deeper analysis of the results obtained is proposed to determine the turbulence level of the flow ahead the flame front.

4. Application of the direct method to aluminum flames

4.1 Presentation of the aluminum flame propagation tests

The experimental setup used for the study of aluminum dust flame propagation has been already described in (Chanut et al., 2018), and is presented on Figure 1. The visualization part of the prototype is a vertical tube of 700 mm height with a 150 mm square-cross section. Aluminum dust is injected in the prototype by discharged of two compressed air vessels through four injection tubes located in the corners of the prototype.

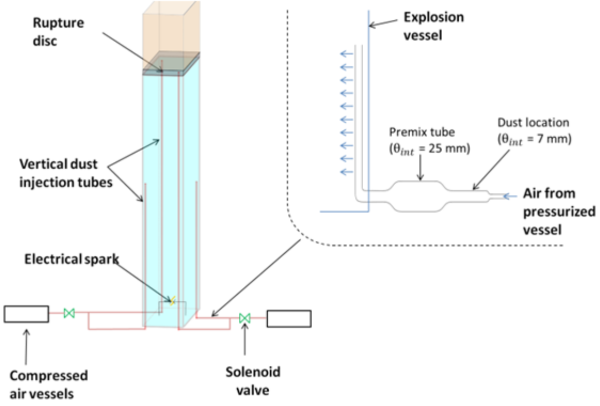

Figure 1: Sketch of the experimental setup

The dust cloud is then ignited by an electrical spark between two tungsten electrodes located at the bottom of the prototype. For the experiment presented hereafter, the energy of the spark is around 15 J. From this ignition spark, the flame propagates upward inside this tube; then the flame is conducted through an evacuation tube. Aluminum dust with mean diameter of 5 microns is studied in the following example.

4.2 Presentation of the optical setup

For estimating the turbulent burning velocity with this “direct method”, two velocities have to be measured: the flame propagation velocity and the flow velocity ahead of the flame front. A first high-speed camera is used to visualize the flame front propagation, and thus to deduce the flame propagation velocity. A second optical system is used to measure the flow velocity ahead the flame front, based on particle image velocimetry (PIV).

PIV is a non-intrusive optical technique used to visualize the movement of fluids. With this technique, 2D maps of velocity on a plane of the flow are obtained. The optical setup consists on a laser generating a laser sheet corresponding to the plane of measurement. A camera located perpendicular to this sheet records the movement of the particles in this plane. Each image recorded by the camera is divided in different interrogation areas (IA). Movement of particles inside each interrogation areas between two successive images is deduced by a correlation algorithm. For PIV measurement, the flow has to be seeded with particles. In this study, the seeding particles are the particles of the combustible dust.

However, some difficulties appear while implementing this method experimentally, because of intrinsic characteristics of aluminum flames. Indeed, aluminum flame is a fast and very luminous phenomenon. Moreover, a dense cloud is needed to observe flame propagation; so the laser beam is attenuated while passing through the cloud.

For the PIV setup, the camera has to record the laser light dispersed by the cloud; not the light emitted by the flame. For this purpose, a pulsed laser is used; to have the maximum of energy during the minimum of time. With this pulsed laser, by decreasing the camera exposure time, the flame light recorded by the camera is limited. A band-pass filter, centered on the wavelength of the laser is also located in front of this camera to limit the flame light recorded. To increase the laser power, which is attenuated by the dense dust cloud, the two pulses (from the two cavities of the pulsed laser) are emitted at the same moment.

For the results presented hereafter, the laser used is a Litron pulsed laser (30 mJ at 1 kHz, λ= 527 nm). To have sufficient energy on the laser sheet, the frequency is fixed to 2 kHz. The corresponding “PIV camera” is a Phantom V711 high speed camera, with a resolution of 1280x800 pixels at the frequency of 2 000 fps. This camera is equipped with a Nikkor lens with a focal of 105 mm and an aperture of f/2.8. The “flame camera” is a Phantom V2512 camera with the same resolution of 1280x800 pixels at this frequency of 2000 fps. This camera is equipped with a 70-300 mm Nikkor lens, with an aperture of f/22. The exposure time of both cameras is fixed at 1µs. For analysis purpose, these two cameras record the same field of view (height: 12 cm; width: 7,5 cm). For these first results and analysis, only the upper centered part of this field of view is analyzed (height: 4 cm; width: 2,5 cm).

4.3 Analysis method

From the images obtained with both the “PIV camera” and the “flame camera”, the following steps allow the determination of the turbulent burning velocity (S_u) and the RMS velocity fluctuations (V_{RMS}) in front of the flame front. These steps are schematized on Figure 3.

1) From the images obtained with the “flame camera”, the flame front is detected.

2) From the images obtained with the “PIV camera”, the velocity field is determined. For this step, in a first time, the images are pre-processed to homogenize the light intensity to improve the results from the PIV analysis. Then the PIV analysis is performed with the DynamicStudio software (Dantec Dynamics). For this analysis the size of the interrogation area (IA) is 8x32 pixels, resulting in 34 IA along the horizontal axis.

3) The mean flow velocity (V_{mean}) is then extracted from each vector field. This mean velocity could be related to the global thermal expansion of the burned gases resulting in a global movement of the flow inside the prototype to the open top end. This mean flow is calculated from the IA of the upper horizontal line. From these IA, the mean velocity corresponds to the mean of the vertical component of the velocities.

4) This mean velocity is then subtracted to the velocity field; velocity field is now relative to the mean flow.

5) The velocity vectors just in front of the detected flame front are extracted. For each velocity vector extracted, the corresponding normal to the flame front is deduced from the images obtained by the “flame camera”.

6) As the turbulent burning velocity is defined in accordance to the flame front, as previously noticed in part 3, the previous velocity vector is projected relative to this normal vector; the resulting vector is now (u’,v’).

7) The mean of the v’ (velocity component normal to the flame front) is defined as the burning velocity.

8) In this step, the RMS velocity fluctuations in front of the flame front are estimated. This turbulence is defined in a zone in front of the previous vectors representing the top of the flame front. The height of this zone is defined to be 4 IA. Each velocity vector (u,v) is used for the calculation of the RMS velocity fluctuations; these velocity vectors already result from the subtraction of the global mean flow velocity (step 4). For defining turbulence, mean velocity ($\bar{u}$ and $\bar{v}$) is defined; the mean is here defined as the spatial mean over all the previous IA. Then the RMS velocity fluctuations (V_{RMS}) are obtained from the following formula:

$$V_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(u_i - \bar{u})^2 + \frac{1}{n}\sum_{i=1}^{n}(v_i - \bar{v})^2} \quad (6)$$

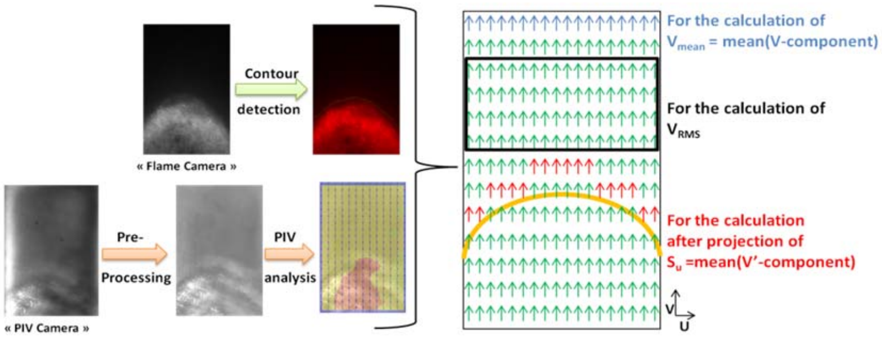

Figure 2: Description of the analysis method

4.4 First results obtained

In this part, first results obtained during an aluminum dust flame propagation test are presented. For this experiment, the aluminum dust concentration is 312 g/m^3. Figure 3 presents the results obtained for the evolution of the turbulent burning velocity in the field of view of the cameras. On this graph, the corresponding evolution of the RMS velocity fluctuations is also plotted. As shown on this figure, the turbulent burning velocity and the RMS velocity fluctuations are fairly constant. The calculation of the mean value of both data gives a turbulent burning velocity of 37 cm/s for RMS velocity fluctuations of 11 cm/s.

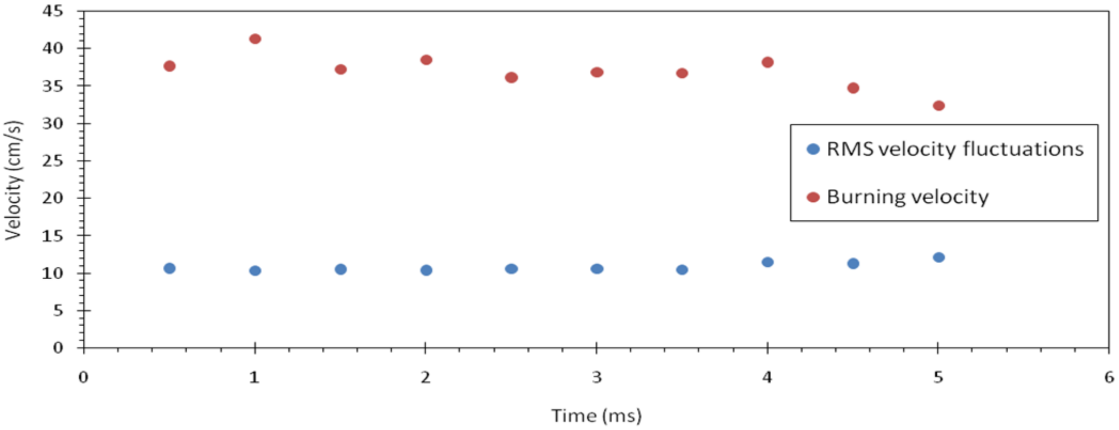

Figure 3: Results of burning velocity and RMS velocity fluctuations

Table 1: Comparison of burning velocity data with the literature

Authors	Apparatus used	Burning velocity (cm/s)
(Goroshin et al., 1996b)	Bunsen burner	20
(Julien et al., 2017)	Counterflow burner	30-40
(Julien et al., 2015)	Unconfined propagation	20
(Goroshin et al., 1996a)	Open tube	30-40
Present study	Open tube	37

This value is coherent with values of the literature, as exposed in Table 1 (adapted of the analysis of Julien et al. (2017)). Indeed, this value is close to the laminar burning velocity of aluminum as the RMS velocity fluctuations are low. Nevertheless, the main advantage of this study is the determination of the corresponding RMS velocity fluctuations. Thus, with this test and this analysis, a first point of the relation between the turbulent burning velocity and the RMS velocity fluctuations is obtained. Other tests, with different RMS velocity fluctuations, are required to obtain more points and thus the final relation.

5. Conclusions

This study focused on the experimental determination of the burning velocity for dust flame propagating in tubes. First, the commonly used “open-tube method” was presented. Some limitations of this method were highlighted; mainly the estimation of the thermal expansion coefficient and the estimation of the 3D flame surface area from 2D images. An alternative method, the “direct method”, was then presented. This latter is based on the measurement of the fresh flow velocity just ahead the flame front. Difficulties of such measurement in the case of aluminum propagating flames were exposed; indeed, aluminum propagating flames are very luminous and fast phenomena. The corresponding analysis method was detailed. With this method, turbulent burning velocity and RMS velocity fluctuations are evaluated.

First results obtained were analyzed and commented. From this first experiment, the mean turbulent burning velocity is 37 cm/s for the corresponding RMS velocity fluctuations of 11 cm/s. This first result is in accordance with the literature. More tests are needed to obtain the relation between turbulent burning velocity and RMS velocity fluctuations. Additional tests will be realized in a longer prototype: with different measurement zones along this new prototype, different RMS velocity fluctuations will be obtained and thus the corresponding burning velocities will be deduced. Indeed, turbulence of the fresh flow increases when the flame propagates inside the prototype because of explosion-induced turbulence. Moreover, in order to deeply study the influence of RMS velocity fluctuations on burning velocities, obstacles will be located inside this longer tube.

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