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Simultaneous Measurement of Burning Velocity and Turbulence Intensity Ahead of the Flame Front during Aluminium Flame Propagation

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Numerical simulations of the flame propagation process are mandatory to predict the consequences of dust explosions. One key parameter of these models is the burning velocity, i.e. the consumption rate of the reactants by the flame front. This burning velocity depends on the characteristics of the mixture and on the characteristics of the flow. Experiments are needed to estimate this burning velocity and to evaluate the influence of the turbulence on this velocity. In this paper, an optical setup is implemented to perform TR-PIV (Time-Resolved Particle Image Velocimetry) measurement during aluminium flame propagation in a vertical tube. Because of the nature of the studied phenomena (luminous flame, propagating flame, dense particle cloud…), performing PIV is challenging. With the analysis method detailed in this paper, the burning velocity and the corresponding turbulence level just ahead of the flame front are simultaneously determined. A preliminary result is presented to illustrate this method. Following this method, the influence of turbulence on burning velocity will be studied.

1. Introduction

Dust explosion is a major risk in industries dealing with powders. Modelling this phenomenon allows the determination of the consequences in case of accidents. Many models used for predicting dust explosions consequences are based on existing models designed for the prediction of gas explosions. These models seem adapted for organic dusts, but not accurate enough for metallic dusts (Kahlili, 2012).
Modelling the consequences of these accidental explosions requires accurate modelling of the flame propagation process. One key parameter is the burning velocity (S_u); representing the consumption rate of the reactants by the flame front. This burning velocity depends on the characteristics of the mixture, via the laminar burning velocity ($S_u°$), and on the characteristics of the flow, especially the turbulence level via for example the RMS fluctuations velocity (V_{RMS}). Many relations between these three quantities have been implemented in models used for predicting gas explosions. One example of this relation is the following one (Dahoe, 2000):

$$\frac{S_u}{S_u{}^0} = 1 + C.(1 + \frac{V_{RMS}}{S_u{}^0})^n \quad (1)$$

Experiments are needed to estimate the link between burning velocity and turbulent intensity. Estimation of the burning velocity, especially for metallic dusts, remains a challenging experimental topic. Different experimental setups and analysing methods are used in the literature to deduce this burning velocity. Some studies focus on the study of stationary flames to measure the burning velocity (Goroshin et al., 1996; Julien et al., 2017). Even if burning velocity can be deduced from the visualization of the flame shape, the flow characteristics do not reflect those due to the propagation of a flame front during an accidental explosion. Furthermore, experiments on stationary flames cannot be used for the validation of simulations of flame propagation during explosions. Other authors perform explosions in closed vessels, for example in the 20-liter

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explosion sphere, to estimate the burning velocity (Dahoe & de Goey, 2003). In general, the burning velocity is deduced from the evolution of pressure over time. During such experiments, turbulence intensity is estimated at the moment of ignition. Different tests with different ignition delays, ie with different initial turbulence intensities, are performed to obtain the link between burning velocity and initial turbulence intensity. As highlighted by Faghih and Chen (2016), assumptions are needed for determining the burning velocity from the pressure evolution over time.

In this paper, a method is proposed to determine the burning velocity by studying the propagation of a flame in a vertical tube. The main advantage of this setup is to study flames that propagate along a main direction, with large optical access. The general method used for estimating the burning velocity from propagating flame is the so-called “open-tube method”. This method calculates the actual combustion velocity from the apparent flame propagation by estimating the thermal expansion contribution. This requires an estimation of the flame temperature to estimate the volumic expansion of burned mixture. In general, the adiabatic flame temperature is used instead of the real flame temperature but may entail an error. Furthermore, turbulence intensity during flame propagation cannot be estimated with this method.

In this paper, the determination of burning velocity is based on the direct measurement of two velocities: the propagation velocity (ie the flame velocity in the laboratory referential) and the unburned flow velocity, avoiding major assumptions about thermal expansion. This method proposes to simultaneously estimate locally the burning velocity and the corresponding turbulence level just ahead of the propagating flame. This turbulence level is due to the propagation of the flame front on the tube, and thus more relevant of the characteristics of the flow that can be obtained for real accidents. These experiments are innovative and challenging by the simultaneous measurement of burning velocity and turbulent intensity in the case of metallic propagating flames which is a tricky procedure; with these data, the coefficients of the equation (Eq. 1) can be determined. Furthermore, they can also be used for validating the modelling of dust flame propagation by a local measurement of the turbulent intensity.

2. Materials

2.1 Presentation of the experimental setup

The prototype presented in Figure 1 is used for studying dust flame propagation. This prototype is constituted of three different sections. Each section is a vertical tube of 700 mm height and 150 x 150 mm square cross-section. Three walls are made of glass to allow the visualization of the flame. The fourth wall can be also made of glass or made of steel if pressure measurement is needed. For the test presented hereafter, the fourth walls of the two upper sections are made of glass. The fourth wall of the lower section is made of wood for inserting the ignition system.

Dust is injected inside a section by the discharge of two pressurized vessels (not represented in Figure 1) connected to four injection tubes located in the corners of the section. Details of the dust injection system can be found in (Chanut et al., 2020). This previous paper describes in detail a prototype constituted of one unique section. In this new prototype constituted of three sections, dust injection systems are implemented in the two lower sections. Thus, dust can be injected only on the two lower sections.

Dust is ignited by an electrical spark between two tungsten electrodes. These electrodes are located 20 cm from the bottom of the prototype. The energy of this spark is 300 J. The spark duration is 1 s.

After ignition, the flame propagates through the three sections before reaching the exhaust at the upper part of the prototype. Thus, the flame propagates upward from the closed bottom end to the open upper end of the prototype.

The aluminium studied has a mean diameter of 6.5 µm. In the test presented hereafter, dust concentration is 750 $g.m^{-3}$.

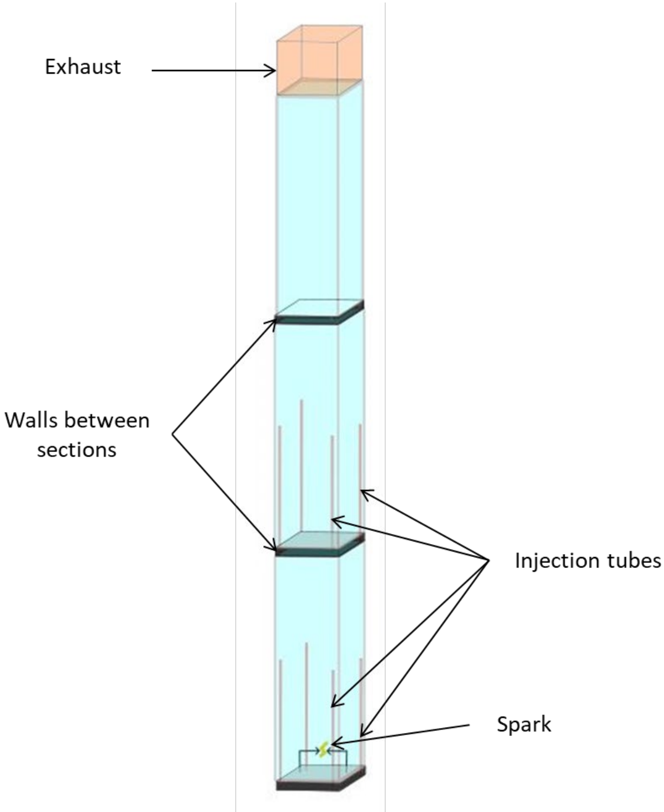

Figure 1: Experimental setup

2.2 Presentation of the optical setup

As previously mentioned, two velocities are measured to estimate the burning velocity: the propagation velocity and the unburned flow velocity. Propagation velocity is determined by the direct visualization of the flame propagation. Unburned flow velocity just ahead the flame front is measured by Particle Image Velocimetry (PIV).

Direct visualization is performed by a high-speed camera recording the flame propagation on the two upper sections. The camera is a Photron SA3 high-speed camera equipped with a Nikkor 17-35 mm. The lens aperture is f/2.8. The data acquisition rate is 7500 fps at a resolution of 1024 x 256 pixels. The exposure time is set to 2 µs.

Performing PIV just ahead of an aluminium dust flame is challenging. Indeed, aluminium dust cloud has to be dense for the flame to propagate. Laser light is thus highly attenuated by this dense cloud of particles. Furthermore, the aluminium flame is very luminous. For PIV measurement, the camera has to record the laser light dispersed by the particles, not the light emitted by the flame front. Furthermore, the flame is propagating at velocities up to 50 $m.s^{-1}$. For all these reasons, TR-PIV (Time-Resolved PIV) has to be implemented. An energetic pulsed laser is used and a bandpass filter is mounted on the high-speed camera used for PIV measurement. This bandpass filter is centred on the wavelength of the laser.

The laser used is a Litron Nd:YAG pulsed laser (30 mJ at 1 kHz). The frequency of the pair of pulses is 1 kHz. The delay between pulses is 46 µs.

The high-speed camera used for this PIV measurement is a Phantom V2512. This camera, synchronized with the pulsed laser, is called “PIV camera” in the following. This camera is equipped with a Tamron 70-300 mm. The lens aperture is f/22. The exposure time is set to 1 µs. The resolution of this camera is 1280 x 800 pixels.

Another high-speed camera records the light emitted by the flame front in the same location as the PIV measurement. This camera is called “flame camera” in the following. This visualization allows defining the flame front on the images obtained by the PIV setup. The “flame camera” is a Phantom V711 equipped with a Tamron70-300 mm. The lens aperture is f/8. The acquisition frequency is 1 000 fps resulting in a resolution of 1280 x 800 pixels. The exposure time is set to 1 µs.

A comparison of an example of images obtained by this high-speed camera and by the PIV camera is exposed in Figure 2. These two cameras are temporally synchronized: the “flame camera” records an image just after (delay of 2 µs) the first image recorded by the “PIV camera”. This image obtained with this ‘flame camera” is thus not affected by the laser.

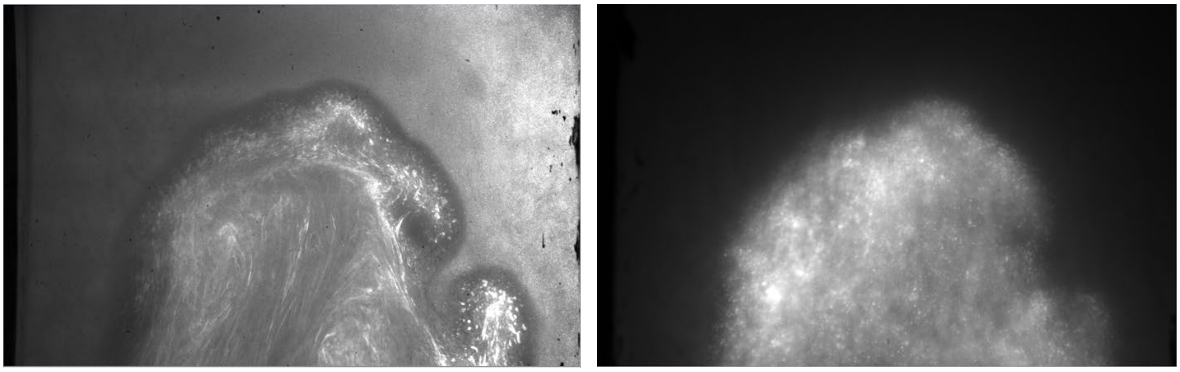

Figure 2. On the left: image obtained by the "PIV camera". On the right: image obtained by the "flame camera"

3. Analysis method

Analysis methods for determining burning velocity and turbulence intensity just ahead of the flame front are explained based on the schema of Figure 3.

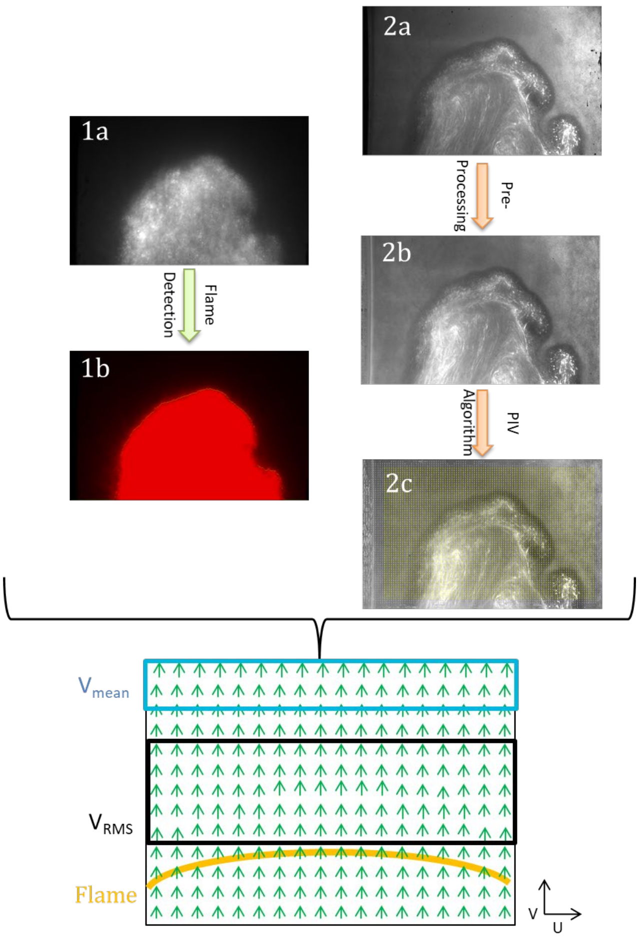

Figure 3: Schema of the analysis method

3.1 Determination of turbulence intensity

From each pair of images recorded by the “PIV camera”, a PIV algorithm is applied to deduce 2D maps of velocity vectors (2 components) using the software Dynamic Studio (Dantec Dynamics). A preliminary step is mandatory to pre-process the raw images (image 2a on figure 3) before performing the PIV algorithm. This preliminary step corrects the non-homogeneity of the grey level of the raw images due to the laser light attenuation by the particles and the difference of laser light intensity between the two laser pulses. PIV algorithm is then applied to these pre-processed images (image 2b on figure 3).
The grid step size of this PIV analysis is 8 x 8 pixels (spatial resolution) resulting in 88 (along the vertical axis) x 141 (along the horizontal axis) velocity vectors calculated for this analysis (yellow vectors in the image 2c in Figure3); the other vectors (located on the edges of the images) are not used for the analysis. The algorithm used is adaptative. The size of the interrogation window used for the correlation calculation is adapted depending on the particle density and on the flow field. For this analysis, the size of the adaptative windows is adapted from 16 pixels to 64 pixels.
Turbulence intensity has to be determined just ahead of the flame front. Flame front location is first determined as the vertical coordinate of the highest point of the flame contour detected. A zone (black square in Figure 3) just ahead of the flame front is used for the calculation of the turbulence intensity. The height of this zone is fixed at 45 interrogation windows.
For calculating the turbulence, a mean velocity has to be evaluated. For each interrogation window and for each velocity component, the mean velocity ($\bar{u}$ and $\bar{v}$) is defined as the spatial mean of the vectors located around this interrogation window. The size of this zone used for the calculation of the mean is 15 interrogation windows along each axis. For each interrogation window, the RMS fluctuations velocity (V_{RMS}) is calculated considering the vectors (u_i and v_i) previously used for the determination of the mean:

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

Global RMS velocity ahead the flame front is then defined as the spatial mean of the previous RMS velocities calculated.

3.2 Determination of burning velocity

With this direct method, burning velocity is based on the direct measurement of two velocities: the propagation velocity and the unburned flow velocity.
From the images obtained by the “flame camera”, the contour of the flame front is extracted. The flame front position is defined as the vertical coordinate of the highest point of this contour. Propagation velocity is then defined as the derivative of the evolution of this position over time.
Unburned flow velocity determination is based on the maps of velocity vectors previously obtained. As exposed in Figure 3, mean unburned flow velocity determination is based on the analysis of the vectors of the upper part of the images. For this analysis, the height of the zone of analysis is 10 interrogation windows. Unburned flow velocity is defined as the spatial mean of the vertical component of these velocity vectors.
Propagation velocity and unburned flow velocity are defined as upwards velocities; they are collinear. Burning velocity is thus defined as the difference between these two velocities.

4. Results

Unburned flow velocity is determined based on the results of the PIV analysis. The evolution of this velocity is estimated while the flame crosses the PIV measurement zone. A constant unburned flow velocity of 22.5 $m.s^{-1}$ is measured.
Images of flame propagation are recorded by the “flame camera” while the flame crosses the PIV measurement zone. Images are also recorded by the SA3 high-speed camera while the flame propagates on the two upper sections of the prototype. Results obtained in the common measurement zone (i.e. in the PIV measurement zone) are fairly close. A mean propagation velocity of 25 $m.s^{-1}$ is obtained.
Burning velocity is finally deduced from these two velocities. This burning velocity is 2.5 $m.s^{-1}$.
Turbulent intensity just ahead of the flame front corresponding to this burning velocity is then estimated. Applying the analysis method previously exposed, RMS velocity is 1.35 $m.s^{-1}$. Only three maps of velocity vectors are analysed for this turbulence estimation. These three images correspond to the instants when the flame reaches the PIV measurement zone; with these images, the turbulence intensity just ahead of the flame front is determined. Other images of flame propagation obtained in this PIV measurement zone were not

considered for this determination of the turbulence intensity as not enough interrogation windows are obtained in front of the flame front (mean velocity calculation is based on 45 windows interrogations along the vertical axis). This preliminary experiment and analysis lead to the local simultaneous estimation of the burning velocity and the turbulence level just ahead of the flame front. The burning velocity obtained is 2.5 $m.s^{-1}$ at the RMS velocity of 1.35 $m.s^{-1}$.

5. Conclusions

An innovative method has been proposed to simultaneously measure the burning velocity and the corresponding turbulence level in front of the flame front during aluminium dust flame propagation. Contrary to the widely used "open-tube method", the estimation of the burning velocity is not based on an approximation of the flame temperature. The burning velocity determination is based on the direct measurement of two velocities: the propagation velocity and the unburned flow velocity. In this paper, the flow velocity is studied by PIV (Particle Image Velocimetry). Performing PIV measurement in front of a propagation aluminium dust flame is challenging. Because of the nature of the experiments (dense particle cloud, luminous flame, propagating flame…), TR-PIV (Time-Resolved PIV) is implemented using a high-speed camera and pulsed laser with high repetition rates. With this PIV setup, turbulence intensity ahead of the flame front can also be evaluated. The corresponding analysis method and preliminary result on a first experiment have been presented.
This simultaneous estimation of burning velocity and turbulence intensity can be used for estimating the relation between these two quantities. This relation is fundamental for modelling flame propagation in case of real accidents. Furthermore, these experiments of propagating flames can also be used for the validation of numerical simulations.
Other experiments will be realized with this optical setup and this analysis method. Different data on burning velocity, and on the corresponding RMS velocity, will be obtained and used to determine the relation between these two quantities to be implemented in numerical models. PIV measurement zone will be located at different heights to obtain different turbulence levels. Indeed, as the flame propagates in the tube, the turbulence intensity should increase resulting in an increase of the corresponding burning velocities.
Furthermore, to obtain higher turbulence intensities, obstacles will be located inside the prototype. These experiments with obstacles will also be used to validate future numerical simulations.

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