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Direct determination of turbulent burning velocity during aluminum flame propagation: A comparison of three experimental methods

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ABSTRACT

Burning velocity is a key parameter of main flame propagation models. However, its experimental determination while studying propagating dust flame is still challenging. In this work, aluminum flame propagation in a vertical tube is studied. Two aluminum powders with median diameters of 6.2 and 20.7 μm are analyzed for different equivalence ratios with air. The main objective of this work is to compare the methods commonly used in the literature to determine the burning velocity in the case of propagating flames. One of these methods is based on the estimation of the thermal expansion coefficient. This article focuses first on the estimation of this coefficient and presents the limits of considering the adiabatic flame temperature for its estimation. As detailed in the paper, these methods have some limitations and are therefore compared with an innovative method based on a local direct determination of the burning velocity. This local method is based on the measurement of the unburned flow velocity just ahead of the propagating flame front by Time-Resolved Particle Image Velocimetry (TR-PIV). The methods commonly used in the literature mainly underestimate the burning velocity when compared with the local method. The local method is then used to study the influence of the particle size distribution and the equivalence ratio on the turbulent burning velocity. Firstly, we observe that the turbulent burning velocity increases while the flame is propagating in the vertical tube. Furthermore, the turbulent burning velocity with the 6-μm powder is higher than with the 20-μm powder.

1. Introduction

Metal combustion, especially aluminum dust combustion, is widely studied as it is involved in different scientific fields (process safety, aerospace propulsion, defense). Fundamental understanding of dust combustion is therefore required to prevent accidental explosions and improve the performance of propulsion systems (Han et al., 2017). However, modeling metal dust flame propagation is still challenging due to the complex processes governing this multi-phase combustion and the inherent difficulties in performing experiments on dust flame propagation (Goroshin et al., 2022). Modeling flame propagation is mandatory to predict the consequences of accidental explosions. One key parameter of these flame propagation models is the burning velocity, i.e. the consumption rate of the reactants by the flame front. Besides, modeling the flame propagation requires modeling the combustion dynamics but also the induced flow and turbulence. Thus, the evolution of the turbulent burning velocity while the flame is propagating has to be determined.

Experimental determination of this turbulent burning velocity is challenging, particularly for metallic flames. A first setup commonly used to estimate the burning velocity is the burner. In this case, the burning velocity is deduced from the visualization of the shape of the stationary flame (Goroshin et al., 1996; Julien et al., 2017). A confined explosion sphere can also be used to obtain the burning velocity in case of propagating flames. The burning velocity is deduced from pressure data (Dahoe and de Goey, 2003); as highlighted by Faghih and Chen (2016), the estimation of the burning velocity from the evolution of the pressure is based on some assumptions. Furthermore, the flame propagation process inside the explosion sphere is difficult to observe and study.

To develop and validate flame propagation models, the propagation of flames inside tubes can be studied. Andrews and Bradley (1972) proposed a method for estimating the burning velocity while studying propagating flames inside tubes, called the “tube method” in this article. This method is based on the visualization of the flame propagation, the estimation of the flame surface area and the measurement of the mean unburned flow velocity averaged over the tube cross-sectional area.

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Other authors adapted this method to estimate the burning velocity without measuring the unburned flow velocity (Di Benedetto et al., 2011; Khalili, 2012). This method is based on the estimation of the thermal expansion coefficient; this coefficient is defined as the ratio between the unburned mixture density and the burned mixture density. This method is called the "thermal expansion method" in this paper. The estimation of the thermal expansion coefficient is an important point, detailed in this paper. For both methods, the accurate estimation of the 3D flame surface area is tricky and can lead to errors up to 20 % (Andrews and Bradley, 1972). An innovative direct local method has been proposed in a previous paper (Chanut et al., 2022), called the "direct method" in this article. This method is based on the measurement of the unburned flow velocity just ahead of the propagating flame front by Time-Resolved Particle Image Velocimetry (TR-PIV). This method consists of a local estimation of the burning velocity at the top of the flame front, whereas the two other methods are global estimations of the burning velocity assuming a constant burning velocity over the tube cross-sectional area.

In this article, aluminum flame propagation in a vertical tube is studied. Two aluminum powders with different particle size distributions with a median diameter of 6.2 and 20.7 μm are analyzed for different equivalence ratios with air. This article focuses first on the estimation of the thermal expansion coefficient. Results from preliminary experiments are presented to estimate this coefficient; these results are compared with previous estimations proposed in the literature. Then, the turbulent burning velocity is obtained by using the three methods: "tube method", "thermal expansion method" and "direct method". Finally, the results obtained with the direct method are detailed and discussed to investigate the influences of particle size distribution and equivalence ratio.

2. Experiments

2.1. Experimental setup

The setup is a square-cross section vertical tube divided into three different sections of 700 mm height and 155 × 155 mm cross-section (Fig. 1). The walls are made of glass to allow the visualization of the flame propagation process. During the experiments, dust is injected in the two lower sections by discharge of pressurized vessels connected to four injection tubes located in the corners of the section. Special attention has been paid to the design of the injection tubes to obtain a homogeneous cloud, especially along the vertical axis (axis of flame propagation). Details about the design of the injection tubes and the method for characterizing the initial dust cloud can be found in (Chanut et al., 2020). Dust concentration is determined by weighting the dust inside the injection tubes before and after each experiment. Dust is ignited by an electrical spark between two tungsten electrodes located inside the lower section of the prototype. After ignition, the flame propagates upward from the closed bottom end to the open upper end of the prototype. More details on the setup can be found in (Chanut et al., 2022).

In these experiments, two powders of aluminum are studied. Fig. 1 shows the particle size distributions of the two powders. The median diameters of each powder are 20.7 μm and 6.2 μm; characteristic diameters describing these particle size distributions are detailed in Table 1. In the following, the two powders are called "20-μm powder" and "6-μm powder" respectively.

For each particle size distribution, three dust concentrations are studied. They are defined in terms of equivalence ratio, which corresponds to the ratio of the actual dust concentration and the stoichiometric concentration. The value of the stoichiometric concentration is here estimated to be about 310 g m^{-3}. For the 20-μm powder, fuel-rich mixtures are studied corresponding to equivalence ratio of 1, 1.2 and 1.4. With fuel-lean mixtures, difficulties for igniting the 20-μm powder mixtures are observed. For the 6-μm powder, fuel-lean mixtures are studied corresponding to equivalence ratio of 0.8, 0.9 and 1. For each experimental configuration (defined by a particle size distribution and an equivalence ratio), two tests are carried out.

2.2. Optical setup

Two optical techniques are implemented to analyze the flame propagation process: the direct visualization technique and the PIV (Particle Image Velocimetry) technique. The direct visualization technique records the light emitted by the flame front by using a high-speed camera. The PIV measures the velocity of the flow field, seeded with the aluminum particles, by using a high-speed camera synchronized with a laser. Direct visualization technique is widely used to visualize the propagating flame. However, the flow field ahead of the flame front is rarely studied in experimental works, especially in front of dust flames, because of the difficulty to implement this technique. Nevertheless, a TR-PIV (Time-Resolved PIV) setup has been successfully implemented to study the unburned flow just ahead of the luminous flame front.

Table 1
Characteristic diameters of the particle size distributions of the powders.

	d_{10}	d5$_0$	d_{90}
6-μm powder	3.2 μm	6.2 μm	10.8 μm
20-μm powder	5.6 μm	20.7 μm	39.8 μm

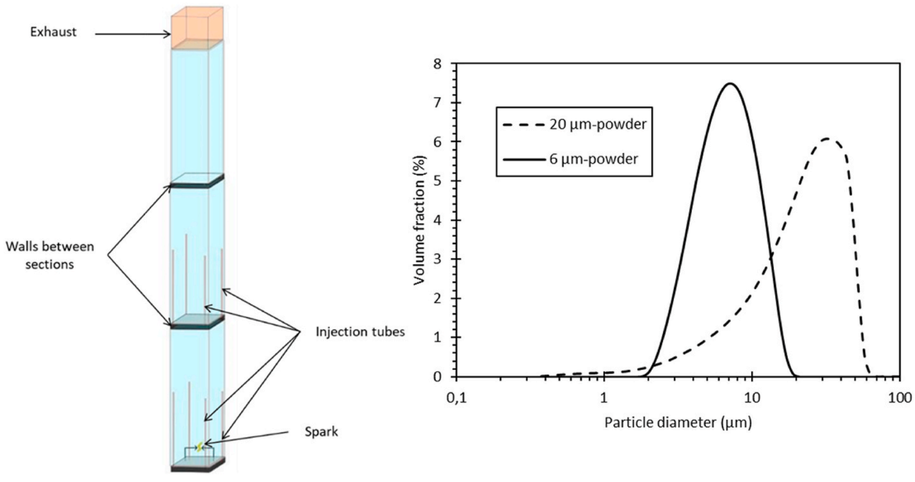

Fig. 1. Experimental setup and particle size distributions of the powders.

A first high-speed camera (Photron SA3) records the flame propagation process by direct visualization technique on the two lower sections of the prototype. The resolution of this camera is set at 1024 x 128 pixels with a frequency of 10,000 fps (frames per second). A second high-speed camera (Photron SA5) records the flame propagation process on the third upper section. The resolution of this camera is set at 1024 x 1024 pixels with a frequency of 7000 fps (frames per second). Using these two cameras the flame front is detected during the propagation along all the height of the prototype.

In addition to this direct visualization technique, two zones of TR-PIV measurement have been implemented. The first zone corresponds to the middle of the second section. For this measurement, a Litron TR-PIV 30–1000 laser (30 mJ at a frequency of 1 k Hz) is synchronized with a Phantom V711 high-speed camera. The second zone corresponds to the top of the prototype. For this measurement, a Litron TR-PIV 15–1000 laser (15 mJ at a frequency of 1 k Hz) is synchronized with a Phantom V2512 high-speed camera. For each PIV measurement, the time between each double image (time between two successive velocity vectors) is 1 ms. The size of each PIV measurement zone is around 15.5 cm × 10 cm. The resolution of the images is 1280 x 800 pixels.

3. Methods: determination of the burning velocity

The objective is to determine the turbulent burning velocity from these experimental data. Three methods are compared: the “tube method”, the “thermal expansion method” and the “direct method”. These three methods are presented on the next subsections.

3.1. *“Tube method”*

In our case of a flame propagating from the open bottom end to the closed top end of a vertical tube, the “tube method” is based on the following expression (Andrews and Bradley, 1972):

$$S_u = \frac{a}{A}.(V_p - U_g)$$

where S_u is the burning velocity, V_p is the flame propagation velocity (i.e. the flame speed in the laboratory referential), U_g is the mean unburned flow velocity averaged over the tube cross-sectional area, a is the tube cross-sectional area, A is the 3D flame surface area. For our experiments, the 3D flame surface area is deduced from the images of flame propagation obtained by direct visualization of the light emitted by the flame front. 2D images are obtained; therefore, the flame shape in the perpendicular plan is approximated with ellipses as explained in details in (Chanut et al., 2020)

U_g is deduced from the PIV data. It is defined as the vertical component of the mean flow velocity averaged over the line located at the top of each PIV zone. This method is implemented only for the experiments with the 20-μm powder. With the 6-μm powder, velocity vectors on all the depth of the PIV zones are not obtained due to the quality of the TR-PIV images. Indeed, the laser light is attenuated while passing through the highly concentrated cloud of aluminum particles; thus, velocity vectors are difficult to deduce by the PIV algorithm in the highly attenuated zones.

3.2. *“Thermal expansion method”*

The “thermal expansion method” is adapted from the “tube method”. For this method, the unburned flow velocity is not measured. This method is based on the following expression (Di Benedetto et al., 2011):

$$S_u = \frac{V_p}{\chi}.\frac{a}{A}$$

where χ is the thermal expansion coefficient defined as:

$$\chi = \frac{\rho_u}{\rho_b}$$

To implement this method the thermal expansion coefficient has to be estimated. Di Benedetto et al. (2011) studied the flame propagation of nicotinic acid dust. They calculated this thermal expansion coefficient as the ratio of the burned mixture temperature to the unburned mixture temperature. However, this equality is not exact for such solid powders devolatilizing before combustion. These authors approximated the burned mixture temperature to the adiabatic flame temperature.

Altman and Pantoya (2024) discussed the estimation of this thermal expansion coefficient for metal particles. They explained that thermal expansion coefficient is overestimated while considering adiabatic flame. Furthermore, the discrete nature of the aluminum dust flame leads to another overestimation of the thermal expansion coefficient in literature. These authors estimated the thermal expansion coefficient from previous experiments conducted by Lomba et al. (2019). They obtained a thermal expansion coefficient of about 5.5 from these experiments, much lower than the value of about 12 obtained while considering an adiabatic flame.

Preliminary experiments were conducted to estimate this thermal expansion coefficient. For this purpose, one section of the prototype has been isolated and slightly modified. With this new experimental setup, upward flame propagations from the open bottom end to the closed top end of the tube were studied. From a mass balance, the following expression is used to determine the thermal expansion coefficient:

$$\chi = \frac{\rho_u}{\rho_b} = \frac{V_p + U_g}{V_p}$$

Here, U_g is the flow velocity of burned mixture exiting the bottom of the prototype and is estimated by performing the PIV algorithm on the combustion products exiting the bottom end of the prototype. This equation is obtained by assuming a constant propagation velocity and unburned flow velocity over the cross-section of the prototype. For these experiments, with the 6-μm powder, a thermal expansion coefficient of about 5.5 is obtained, in accordance with the value proposed by Altman and Pantoya (2024).

3.3. *“Direct method”*

The “direct method” is based on the measurements of the propagation velocity and of the unburned flow velocity just ahead of the propagating flame. At the top of the flame front, the vectors are colinear thus the burning velocity is defined as the difference between these two velocities. One main difficulty of this method is the accurate measurement of the unburned flow velocity just ahead of the propagating flame, especially in case of metallic dusts. Here, the TR-PIV technique is used to determine the most probable movement of particles between two images separated by a known time delay. With this technique, velocity vectors on a plane of the flow are obtained. The software Dynamic Studio (Dantec Dynamics) is used to perform the PIV analysis.

Fig. 2 shows an example of raw TR-PIV of a propagating flame of the 20-μm powder. A first step of pre-treatment is mandatory to improve the quality of the images before performing the PIV algorithm. Indeed, because of the presence of a dense dust cloud, the laser light is attenuated while passing through the prototype. Moreover, the power of each of the two laser cavities (used to obtain the pair of images analyzed by the PIV algorithm) are not exactly equal. For these two reasons, a first pre-treatment step is performed to uniform the grey levels of the images.

An adaptative PIV algorithm is used to modify the size and shape of the interrogation areas depending on the velocity and concentration gradients. The quality of the images obtained with the powder 20 μm is better for performing the PIV algorithm as the laser light is less attenuated by these larger particles present inside the unburned mixture. Thus, input parameters for the PIV algorithm are slightly different for the images corresponding to this powder. For the images corresponding

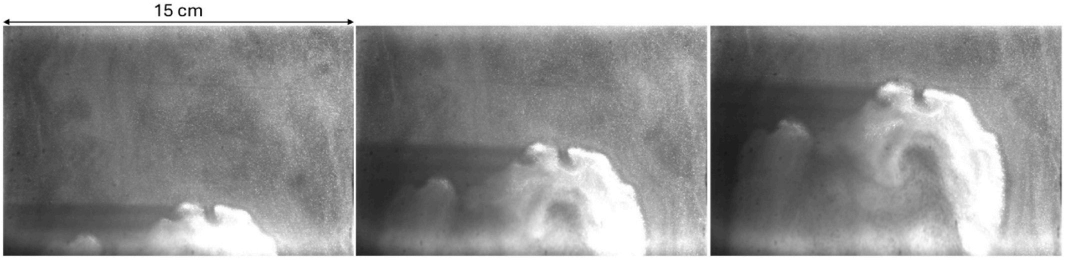

Fig. 2. Examples of raw TR-PIV images with the 20-μm powder (delay between images: 1 ms).

to the powder 20 μm, the distance between two velocity vectors is 0.5 mm while this distance is equal to 1 mm for the powder 6 μm. From these velocity vectors, the burning velocity is deduced; it is defined as the difference between the propagation velocity and the unburned flow velocity just ahead of the flame front.

4. Results and discussion

4.1. Comparison of the different methods

The “tube method” is first compared to the “thermal expansion method” for the experiments with the 20-μm powder (Fig. 3). On this figure and on the following figures, the dotted lines correspond to ± 20 % of variations from the ideal curve $y = x$ (continuous line).

The “thermal expansion method” is applied considering the two values of the thermal expansion coefficient (χ) proposed previously: 12 and 5.5. The value of χ of 5.5 gives results of burning velocity closer to the “tube method”. The value of χ based on the adiabatic flame temperature is thus overestimated leading to an underestimation of the burning velocity. It is thus important to evaluate first this coefficient by studying a stabilized flame on a Bunsen burner, as proposed by Altman and Pantoya (2024), or by studying the upward flame propagation from the open bottom end to the closed top end of a vertical tube, as proposed in this paper.

The “thermal expansion method” gives results in accordance with the “tube method”. Measuring the unburned flow velocity can be challenging, therefore the “thermal expansion method” can be preferred. This method is compared to the estimation of the local burning velocity with the “direct method” (Fig. 4). These two methods are applied on the experimental data with the two granulometric distributions. Taking the “direct method” as reference, the “thermal-expansion method” mainly underestimates the burning velocity.

With the “thermal expansion method”, a global estimation of the burning velocity over the flame surface is obtained, whereas the “direct method” is a local estimation of the burning velocity at the top of the flame front. The “thermal expansion method” assumes a constant burning velocity over the flame surface area. However, as mentioned by Andrews and Bradley (1972), this burning velocity is reduced close to the walls. Thus, the “thermal expansion method” underestimates the value of the burning velocity at the top of the flame front.

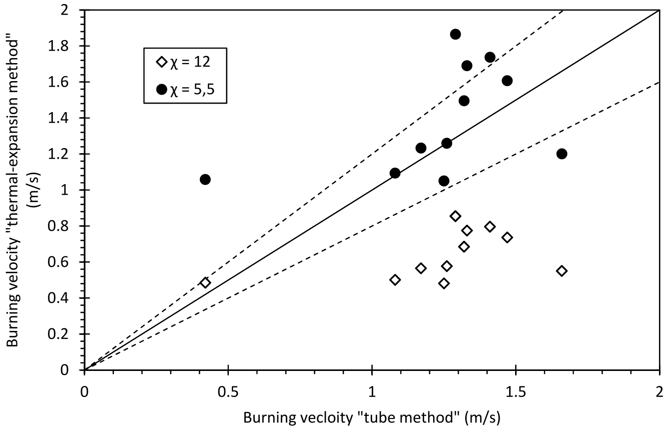

Fig. 3. Comparison of the burning velocity calculated from the “thermal expansion method” and the “tube method”.

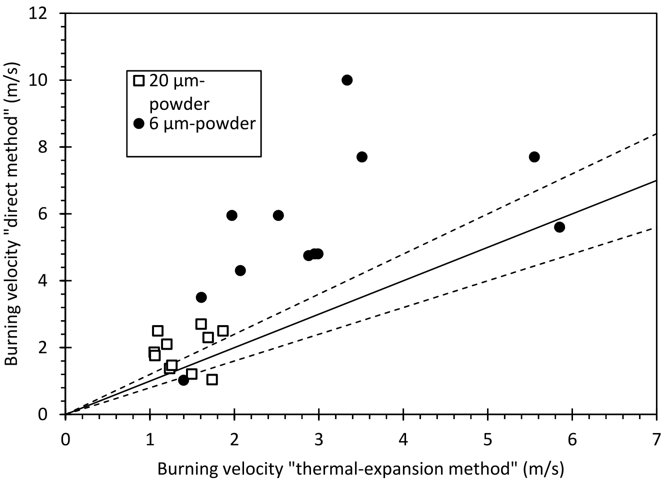

Fig. 4. Comparison of the burning velocity calculated from the “thermal expansion method” (χ = 5.5) and the “direct method”.

Moreover, the evaluation of the real 3D flame surface area is challenging. Fig. 5 shows an example of a zoom on the flame front of an image of the propagating flame. It is difficult to define the real “reactive area” of the flame front, i.e. the flame height (H_1 or H_2 or another value). This value is important for estimating the flame front area. If we consider all the flame surface area until the flame reaches the tube walls (H_2), a high value of the flame surface area is obtained resulting in a lower value of the burning velocity.

Due to the difficulties for estimating the flame surface area and the global nature of the burning velocity calculated with the “thermal expansion method”, the local “direct method” is preferred for estimating the burning velocity at the top of the flame front.

4.2. Analysis of the turbulent burning velocity: “direct method”

The “direct method” is used to determine the burning velocity for the different experimental configurations. First, Fig. 6 shows the relation between the burning velocity and the propagation velocity for all the experimental configurations and for both PIV measurement zones. The black line represents the best fit of these experimental points with an affine function. An increase of the propagation velocity corresponds to an increase of the burning velocity.

Analysing separately the results of both powders, we can observe that the coefficient of the best fit for each granulometric distribution is slightly different. For the 20-μm powder, the value of the slope is 0.121 while this value is 0.156 for the 6-μm powder. This difference can be due

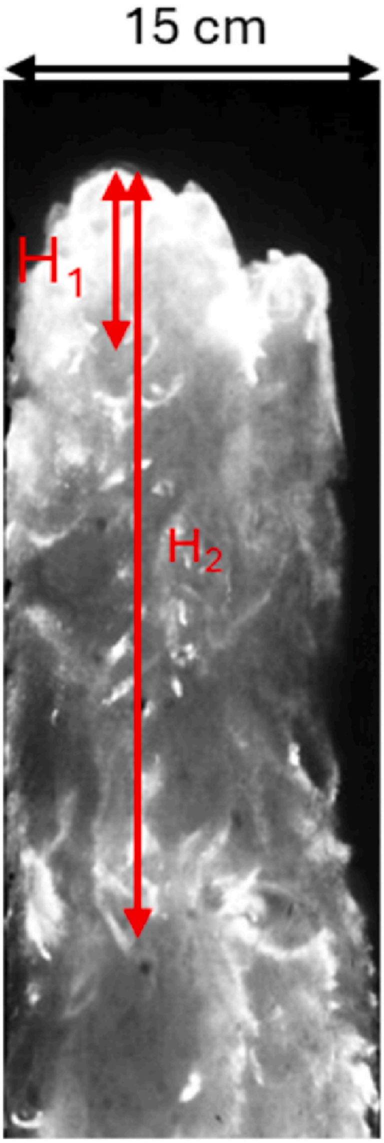

Fig. 5. Zoom on the flame front of the aluminum propagating flame.

to the difference of granulometric distribution. However, this difference could also be due to the difference of equivalence ratio for both granulometric distribution; indeed, fuel-lean mixtures of the 6-µm powder are studied while fuel-rich mixtures of the 20-µm powders are studied.

Fig. 7 shows the values of the turbulent burning velocity determined with the "direct method" for all the experimental configurations and for both PIV measurement zone. As expected, the burning velocity with the 6-µm powder is higher than with the 20-µm powder. This observation can be explained by an increase of the specific surface area, corresponding to an increase of the reactive surface, with finer particles. This result is in accordance with other results from the literature (Danzi et al., 2021).

Moreover, the values of burning velocity determined while the flame passes on the PIV measurement zone 2 are higher compared to the PIV measurement zone 1. The PIV zone 1 is located at the center of the second section while the PIV zone 2 is located at the top of the third section of the prototype. Thus, the burning velocity increases while the flame propagates inside the vertical tube. This increase could be due to an increase of turbulence due to the induced unburned flow ahead the flame front. With this TR-PIV setup, measurements of the local turbulence while the flame propagates is possible as already proposed in a previous paper (Chanut et al., 2022).

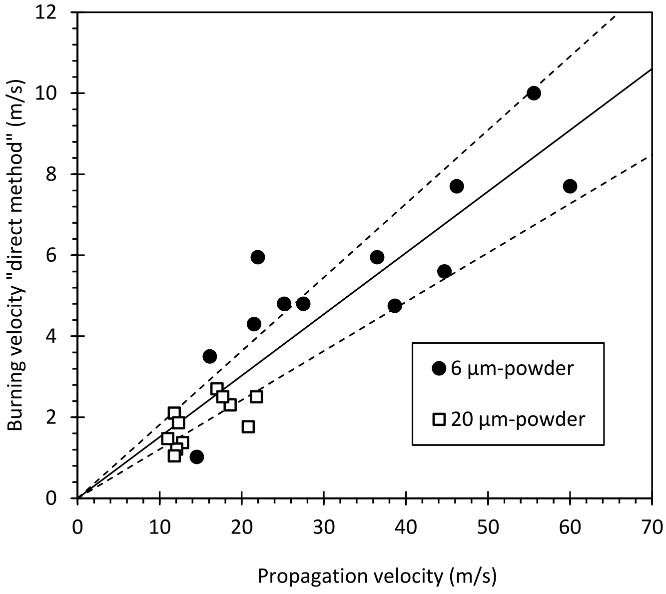

Fig. 6. Relation between burning velocity and propagation velocity.

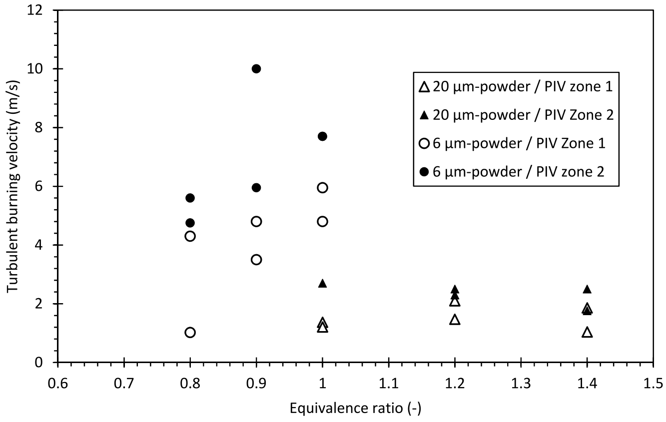

Fig. 7. Turbulent burning velocity as a function of the equivalence ratio for both granulometric distribution.

Analyzing the fuel-lean mixtures of the 6-µm powder, an increase of the burning velocity with the equivalence ratio is observed; this increase can be due to an increase of the quantity ofdust participating to the combustion, increasing the global reactivity of the mixture. On the contrary, a quite constant behavior of the burning velocity with the equivalence ratio is obtained while analysing the fuel-rich mixtures of the 20-µm powder; in this case, additional powder does not increase the global reactivity of the mixture and can absorb some part of the energy of the combustion.

5. Conclusions

Aluminum flames propagating in a vertical tube have been studied. The main objective of the present study was to study the turbulent burning velocity of these propagating flames. Indeed, the burning velocity is an important input parameter of numerical models used for predicting the consequences of accidental explosions. For this purpose, a novelly developed method has been implemented to determine this burning velocity: the "direct method".

Two other methods usually used in the literature have also been implemented: the "global method" and the "thermal expansion method". One method is based on the thermal expansion coefficient.

This paper discusses the determination of this coefficient and its influence on the burning velocity results. An experimental method for estimating this coefficient was proposed; this method is based on the observation of the propagation of the flame in an open tube. The results from this method are equal to the results obtained in the literature while studying stabilized flames. The comparison of the results obtained with the "thermal expansion method" and the "global method" confirms the importance of using the value of the thermal expansion coefficient proposed in this paper. The method generally used in the literature for determining this coefficient is based on the hypothesis of a uniform flame front with a temperature equal to the adiabatic flame temperature. This method leads to an overestimation of the thermal expansion coefficient and an underestimation of the burning velocity.

The innovative "direct method" is promising to determine the local burning velocity of propagating dust flames. Indeed, the two other methods used in the literature are based on the hypothesis of a constant burning velocity over the flame surface, while this velocity is lower close to the walls (Andrews and Bradley, 1972). Moreover, the 3D flame surface area has to be evaluated to implement these methods. Due to the complex geometry of the flame front and the difficult definition of the burning zones, this estimation is challenging.

The "direct method" is here based on a TR-PIV (Time-Resolved Particle Image Velocimetry) setup. With this setup, the evolution of the local unburned flow velocity and of the local turbulence can be obtained. These values are mandatory for accurately validate future numerical simulations of propagating flames. Moreover, the local turbulence just ahead the flame front can be deduced from these TR-PIV data. Therefore, the relation between turbulence and burning velocity can be determined. This relation is an important input parameter of numerical models of flame propagation.

CRediT authorship contribution statement

Clement Chanut: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Farès Saad Al Hadidi:** Investigation, Methodology, Writing – review & editing. **Frédéric Heymes:** Methodology, Supervision, Writing – review & editing. **Ernesto Salzano:** Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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