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Flame propagation and flow field measurements in a Hartmann dust explosion tube

Sepideh Hosseinzadeh [a], Maarten Vanierschot [c,*], Frederik Norman [b], Filip Verplaetsen [b], Jan Berghmans [a]

[a] University of Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, B-3001 Heverlee, Belgium
[b] Adinex NV, Brouwerijstraat 5/3, B-2200 Herentals, Belgium
[c] University of Leuven, Mechanical Engineering Technology TC, Campus Group T, A. Vesaliusstraat 13, B-3000 Leuven, Belgium

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ABSTRACT

In this paper both the flame structure and propagation velocities of zirconium and lycopodium dusts are studied experimentally in air. The measurements were conducted in a Hartmann tube and a high-speed CMOS camera was used to record the images of the flame. The results show that the zirconium flame has a spherical shape, whereas the lycopodium flame has a very complex structure which makes flame speed calculation difficult and the lycopodium flame speed needs to be determined through statistical averaging of multiple measurements. This discrepancy between the flame structure of lycopodium and zirconium is attributed to the flame speed. In case of lycopodium, the flame speed is much lower, which makes the flame structure and propagation very sensitive to turbulent fluctuations of the flow field at the time of ignition. To reveal the structure of the flow field in the Hartmann tube prior to ignition, Time-Resolved Particle Image Velocimetry (TR-PIV) was used. The data of the PIV measurement shows the existence of large turbulent zones, which decay in time. These turbulent structures have a large influence on the flame propagation and therefore, it was concluded that flame speed measurements in a Hartmann tube can only be reliable for powders with a high flame speed.

1. Introduction

Most industrial processes, involving handling or producing powders, are subjected to dust explosion hazards. In order to prevent these, identifying the explosion characteristics, such as the explosion sensitivity and the explosion severity is of considerable importance. Explosion sensitivity refers to the minimum ignition energy (MIE) and the minimum ignition temperature (MIT). The Hartmann tube is a well-known apparatus for measuring the MIE in accordance with the European standard EN 13821 [1]. The explosion severity of dust/air mixtures strongly depends on the velocity of the flame. Various parameters such as particle size, dust concentration, turbulence, delay time and ignition energy have a significant effect on the flame propagation velocity. Several studies have been devoted to the flame propagation mechanism in dust-air mixtures. Most of them use a square cross-section tube [2–4]. Gao et al. [3] investigated the flame propagation of three types of monobasic alcohols with different volatile content in a half-closed vessel. Their results showed that dusts with a higher volatile content would propagate faster and emit more light in comparison with less volatile dusts. Yin et al. [4] studied the flame propagation and the temperature profile of zirconium in a combustion chamber with a square cross-section. Their data indicate that the flame speed is a linear function of temperature. Kern et al. [5] examined the effect of reduced pressure on the flame propagation. Their results show that in addition to the dust concentration, the initial pressure has a significant effect on the flame speed. Another important factor in flame propagation is the location of the ignition source. Eckhoff et al. [6] studied the effect of ignition source position on dust explosion indices in a closed vessel. The data obtained shows that the pressure rise reduces as the ignition source moves towards the top of the vessel.

The particle suspension aerodynamics is another important factor in the dust flame propagation [7]. A detailed insight into the complex process of dust dispersion can be obtained by Particle Image Velocimetry (PIV). Many researchers focused on studying the flow structure using PIV, but only a few of them used a Hartmann tube [8,9]. Gao et al. [8] studied the motion behaviour of unburned particles ahead of the flame front in a hexadecanol dust explosion. Considering the complicated structure of the flame, they concluded that the maximum velocity of unburned particles occurs at 4.2 mm before the flame front. Their results also demonstrate that when the distance from the flame to the particle is larger than 24 mm, the particles settle down with a small velocity. Cuervo et al. [9] investigated the particle behaviour in a turbulent flow in a Hartmann tube

* Corresponding author.
E-mail addresses: sepideh.hosseinzadeh@kuleuven.be (S. Hosseinzadeh), maarten.vanierschot@kuleuven.be (M. Vanierschot).

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of square cross section. They reported that the mean horizontal velocity in the tube is equal to zero. All these works provide some notable insights into the flame propagation of dust particles and help to understand the complicated process of dust combustion. These studies revealed that the flame propagation mechanism strongly depends on the combustion chamber used. Nonetheless, the flame propagation process in the Hartmann tube is still unknown.

The primary objective of this paper is to show and compare the flame propagation of two different dusts with different explosion severity in the Hartmann tube. Particular attention is given to the effect of the ignition source location. This work also investigates how the flow field prior to ignition changes in the Hartmann tube. To do so, Particle Image Velocimetry is used which gives better insight into the complex behaviour of the flow field. Finally, we use flow velocity and flame speed data of different type of dusts to answer the following questions:

1. How does the flow velocity influence the flame speed?
2. For which type of the dust, the flame speed can be measured in the Hartmann tube?
3. What should be done to have an accurate flame speed value in the Hartmann tube?

The layout of the paper is as follows. In Section 2 the experimental setup and procedure are described. In addition, the PIV setup is also explained in this section. In Section 3 the experimental results obtained by a high-speed camera and the PIV are given. Section 4 contains the summary and conclusions.

2. Experimental approach

2.1. Dust samples

Two different types of dust are used. The first one is zirconium having a high density and being very explosive. The second one is lycopodium with low density. The particle size distributions of the milled and sieved (<63 μm) fractions were determined by means of laser diffraction analysis and the median size (d_{50}) of the sieved samples were 43 and 30.6 μm for zirconium and lycopodium respectively, as shown in Fig. 1.

2.2. Experimental apparatus

The experimental apparatus is the Hartmann tube [10] which is composed of a glass combustion chamber with a volume of 1.2 l, provided with an air nozzle and a mushroom-shaped dust dispersion system (Fig. 2). Dust dispersion is triggered by a compressed air blast at 7 bar(g). The air blast generates considerable turbulence and results in the creation of a dust cloud. A spark is drawn between two electrodes that are made of stainless steel placed at a height of 10 cm above the bottom end. According to the test standard, the spark gap is set at 6 mm. The delay between introduction of the dust and spark production is set at 120 ms. To investigate the influence of the position of the ignition source on the flame speed, the Hartmann tube was also turned upside down. As such, the ignition source is placed 20 cm above the bottom of the tube.

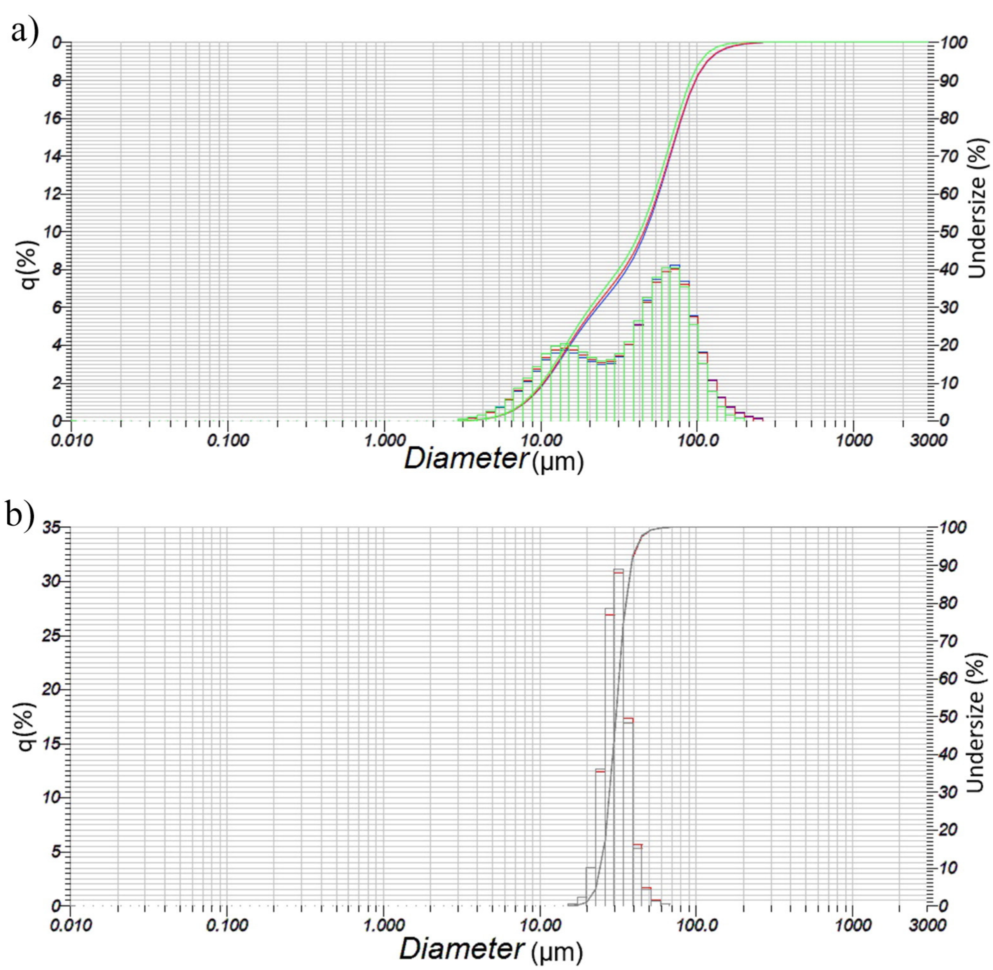

Fig. 1. Particle size distribution (a) Zirconium (b) lycopodium.