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Flame propagation in lycopodium/air mixtures below atmospheric pressure

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A R T I C L E I N F O

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A B S T R A C T

Industrial processes are often operated at conditions deviating from atmospheric conditions. Safety relevant parameters normally used for hazard evaluation and classification of combustible dusts are only valid within a very narrow range of pressure, temperature and gas composition. The development of dust explosions and flame propagation under reduced pressure conditions is poorly investigated. Standard laboratory equipment like the 20 l Siwek chamber does not allow investigations at very low pressures. Therefore an experimental device was developed for the investigations on flame propagation and ignition under reduced pressure conditions. Flame propagation was analysed by a video analysis system the actual flame speed was measured by optical sensors. Experiments were carried out with lycopodium at dust concentrations of 100 g/m^3, 200 g/m^3 and 300 g/m^3. It was found that both flame shapes and flame speeds were quite different from those obtained at atmospheric pressure. Effects like buoyancy of hot gases during ignition and flame propagation are less strong than at atmospheric conditions. For the investigated dust concentrations the flame reaches speeds that are nearly an order of a magnitude higher than at ambient conditions.

1. Introduction

Dust explosion research still faces fundamental problems in the explanation and evaluation of basic parameters of dust explosions, such as minimum ignition energy and temperature as well as those that define flame propagation like flame velocities. Much experimental and theoretical work has already been done but the sheer complexity of the problem still leaves many questions unanswered. Dust explosion testing, for example, still relies on methods that are only able to determine explosion effects under very specific circumstances by so called sum or bulk parameters. In contrary to flame propagation in gas/air mixtures, flame development in dust/air mixtures strongly depends on the physical parameters of the fuel. Particle size and size distribution, chemical composition, moisture, porosity and various other factors influence burning behaviour.

In dust explosion testing, the measurement of flame velocity provides a more detailed insight on the combustion process than the record of pressure/time development measured in the 1 m^3 or the 20 l sphere, which represents a more basic approach in terms of explosion modelling.

The deduction of physical or chemical mechanisms from such experiments is usually not possible. A more knowledge-based approach towards the fundamentals of combustion and ignition would be helpful in the description of dust explosions for example, in complex geometries by mathematical models. A clear understanding of the reaction mechanisms is also crucial for the prediction of dust explosions under non-atmospheric conditions. In contrast, research on dust explosions behaviour under non-atmospheric conditions leads to results that allow a more detailed investigation on parameters influencing explosion reactions. A mechanism of laminar flame propagation through Lycopodium/air mixtures in vertical ducts is described by Han et al. (Han et al., 2000). According to Han the flame develops different zones that exhibit flow patterns and particle concentrations that are slightly different from homogeneous dust/air mixtures. Fresh particles move downwards due to gravitation and enter a preheat zone in front of the leading flame edge. Due to flow patterns in front of the leading flame edge, the particle movement downward stops and the particle moves upwards ahead of the leading flame edge. During its residence time in the preheat zone, pyrolysis takes place and the particle reaches its ignition temperature of around

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425–460 °C (Eckhoff, 1997). The velocity of the flame front is higher than the upward moving velocity of the preheated particles in front of the leading flame edge. Particles heated over their ignition temperature sustain the flame front but leave the leading flame edge still burning. These burning particles form spot flames behind the leading flame edge. Also other researchers Proust, 2006, Han et al., 2000, Krause and Kasch, 2000, Palmer and Tonkin, 1971 dealt with flames propagating through dust air mixtures. Most of the research has been done under conditions at or above ambient pressure. Aim of the present work was to study flames propagating through lycopodium/air mixtures under reduced pressure conditions. Effects on flame speed, flame structure and ignition were of special interest. This paper should contribute to the essentials of dust explosion processes under conditions that deviate from standard ambient conditions. The results gained from these investigations should also lead to a better understanding of dust explosions in general.

2. Experiments

The experimental investigation of dust/air flames is rather difficult because of the fact that homogeneous dust/air mixtures with low turbulence levels are comparatively hard to achieve. Any kind of mixing procedure that creates undefined turbulence levels strongly influences the results of the experiments. Different experimental approaches to determine the flame speed of dust/air flames are known. For the experiments Lycopodium dust was used as a reference substance due to the well investigated combustion characteristics and its physical parameters.

2.1. Basic experimental setup

In the development of dust explosions, turbulence is a key factor in addition to the specific characteristics of the dust itself. Therefore, an experimental setup had to be found that allowed the creation of a homogeneous dust cloud on the one hand and low turbulence conditions on the other hand. Apparatuses described by Krause et al. (Steen, 2000) are able to provide a good particle distribution by using a constant gas flow through a sinter plate under constant but comparatively high turbulence conditions. Other apparatuses use dust feed systems at the top of the testing device, which requires accepting an inferior particle distribution and the disadvantage of not being able to investigate dusts that tend to strongly agglomerate (Proust, 2006; Han et al., 2000; Palmer and Tonkin, 1971). Pre-tests showed that the dispersion of lycopodium in air could be realised quite easily (Kern et al., 2012). Therefore, a top feed arrangement for testing seemed adequate, especially in terms of low turbulence levels. The uniform distribution of the dust over the whole cross section of the tube was monitored by a light extinction of two lasers in a height of 100 mm and 900 mm above the ignition point. The particle distribution was also simulated by computational fluid dynamics (Ansys fluent) and showed that particles are distributed evenly over the whole cross section, starting at 500–700 mm below the feed point. A top feed system also meets the requirements for investigations under reduced pressure conditions because no gas stream is required for dust dispersion.

Experiments in closed vessels often do not allow the visual observation of flame propagation and explosion development. For investigations of flame development, optical systems allowing the determination of flame propagation as well as flame geometry are obligatory. Experiments with pressure levels below atmospheric conditions required a completely sealed combustion section.

Dealing with dust explosion that could create massive damage to persons and equipment experimental safety was a key issue during the experiments. Main considerations have been:

- control of flame spread
- pressure design
- relief systems for uncontrolled pressure build up
- fire protection

For further experiments a main explosion tube (length 2000 mm) made of Plexiglas® was chosen. A tube with an inner diameter of 140 mm and a wall thickness of 5 mm fulfilled the requirements for experiments at atmospheric as well as below atmospheric pressure conditions. Basically the apparatus consists of a bottom section connected to a vacuum pump and housing a spark ignition system, the main combustion tube and a top section with the dust feeding device. Measurement and detection are conducted using an optical system with photodiodes and a video camera for the measurement of the flame shape (Fig. 1). The low frame rate of the video camera did not allow to measure flame speed.

For the determination of the flame speed, five silicon photodiodes (OSRAM BPW 34) were placed along the combustion tube. These show a peak in relative spectral sensitivity at around 850 nm, which covers the top end of the spectrum of visible light (780 nm) and also near infrared. The first photodiode was installed 100 mm above the ignition point, all others in steps of 400 mm. The photodiodes cover a large angular section, which leads to a predetection of the approaching flame front. However, this effect has the disadvantage that the detection signal does not form a sharp peak, which makes the analysis of the signal more difficult and less precise.

The head element houses the dust input system and is equipped with a flame arrestor and an explosion flap. The explosion flap was sealed against the head section via an O-ring sealing. The leaking rate during the experiments was below 1 mbar/s. The dust input is carried out by a screw conveyor that can be regulated by the operating voltage. The input system allows the generation of dust concentrations from 50 g/m^3; to 500 g/m^3; (Lycopodium). During testing the feed system several other dusts have been tested. In

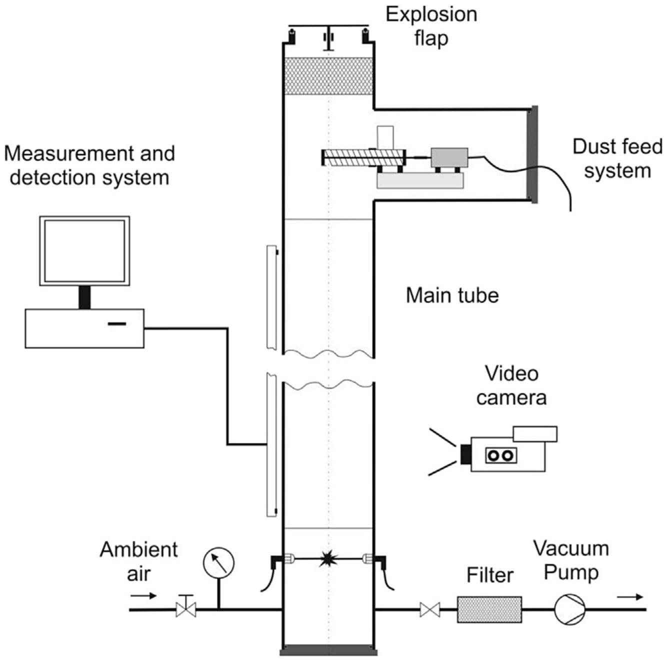

Fig. 1. Testing assembly for the determination of flame speed below atmospheric pressure conditions (Kern, 2013).