The influence of reduced pressure on flame propagation in dust/air mixtures

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Industrial processes are often operated at conditions varying from atmospheric conditions. Safety relevant parameters normally used for hazard evaluation and classification of substances like 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. An experimental device was developed for the investigations on flame propagation and ignition under reduced pressure conditions. Flame propagation was analyzed by a video analysis system the actual flame speed was measured by optical sensors. Experiments have been carried out with lycopodium at dust concentrations of 100 g/m³, 200 g/m³ and 300 g/m³. Flame shape and velocity strongly differs to results at atmospheric conditions. Effects like buoyancy of hot gases during ignition and flame propagation are less strong that at atmospheric conditions. For the investigated dust concentrations flame velocity reaches speeds that are nearly an order of a magnitude higher than at ambient conditions. Results gained from these experiments are contributing to the setup of mathematical models for the description of gas explosions and ignition.

Keywords: flame propagation, dust explosion, pressure dependence

Introduction [1]

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 sum parameters. 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 of the parameters influencing explosion reactions. 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.

The main goal of the present work was to investigate flame propagation under non-atmospheric conditions. Investigations on phenomenological variations of the combustion process itself as well as the parameter of flame velocity were of special interest. The ignition process was also of certain interest, although in-depth research on its mechanisms was not possible with the chosen experimental setup.

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 realise. Any kind of mixing procedure that creates undefined turbulence levels strongly influences the results of the experiments. Different experimental approaches to determine the flame velocity 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.

Basic experimental Setup [2]

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. [3] 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 [4, 5, 6]. Pre-tests showed that the dispersion of lycopodium in air could be realized quite easily [7]. Therefore, a top feed arrangement for testing seemed adequate, especially in terms of low turbulence levels. Various dust concentrations are achievable with proper dust feeding systems. A top feed system also meets the requirements for investigations under reduced pressure conditions because no gas stream is required for dust dispersion.

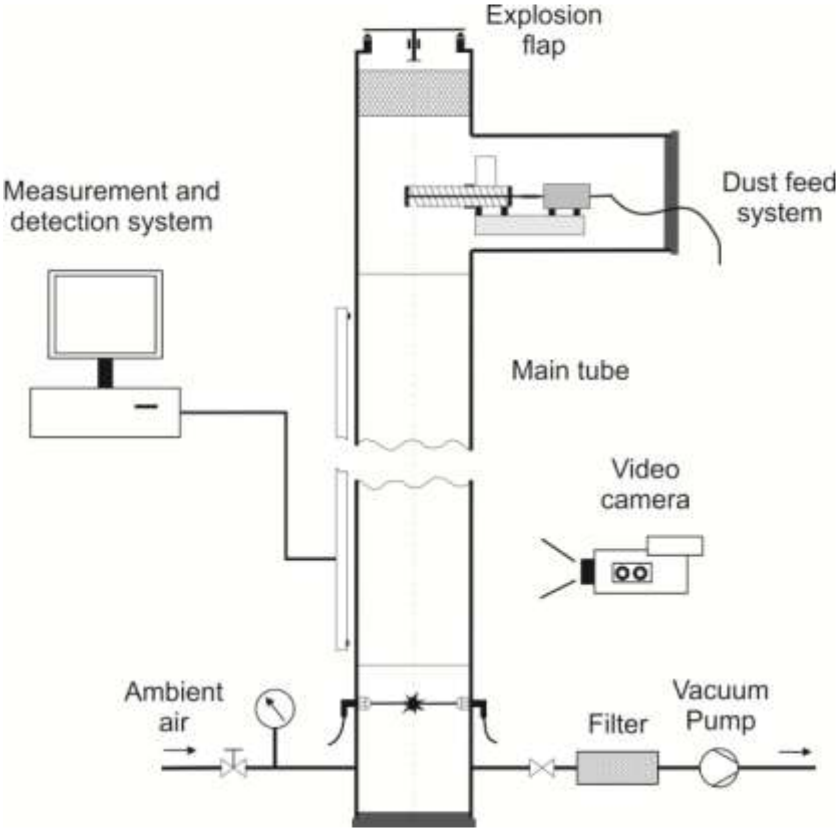

Figure 1: Testing assembly for the determination of flame velocity below atmospheric pressure conditions

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.

For the 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 is conducted using an optical system with photodiodes and a video camera for the measurement of the flame shape (Figure 1).

The head element houses the dust input system and is equipped with a flame arrestor and an explosion flap. 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/m³ to 500 g/m³ (Lycopodium).

The vacuum pump used for the creation of the proper pressure conditions allowed a minimum absolute pressure of around 90 mbar. Due to Bartknecht's [3] findings that an ignition below 20 mbar is not likely and the fact that the spark igniter used provided considerably low ignition energies (~10 mJ), the pump characteristics proved to be satisfactory.

Ignition System

For the ignition of the dust/air mixture inside the combustion tube, a spark ignition system was used. The Ignition source provided an electrical spark with an ignition energy of around 10mJ, which was sufficient for the ignition of the dust/air mixture down to around 250-300mbar. The circuit diagram of the ignition generator is demonstrated in Figure 2.

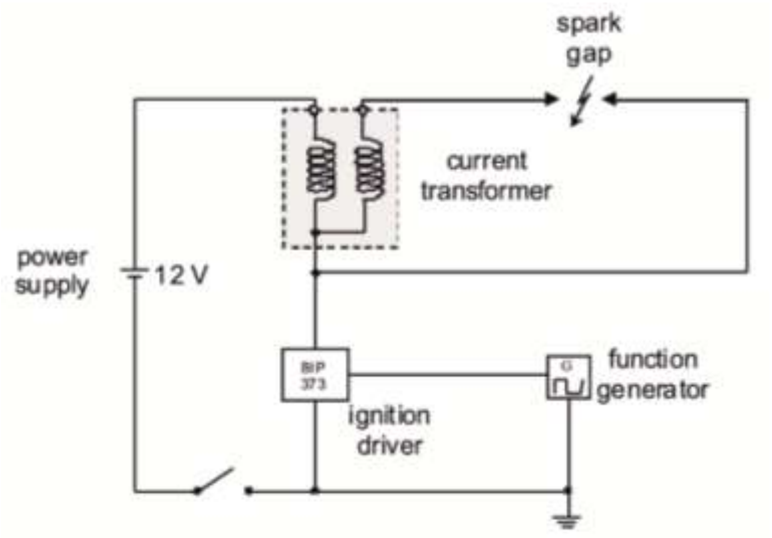

Figure 2: Circuit diagram of the spark generator used for the ignition of the investigated dust/air mixtures.

Two pointed steel-electrodes with a diameter of 2 mm were used as spark igniters. The electrodes were placed such as to form a gap of 6 mm right in the centre of the combustion tube. This electrode assembly is normally also used for dust explosion testing using electrical sparks, like for the determination of the minimum ignition energy [8].

Measurement of flame propagation

Considering the characteristics of the flame, optical systems were used for the measurement of flame propagation and flame geometry. Pre-experiments revealed that flames obtained by lycopodium/air mixtures can be observed visually and emit considerable amounts of yellow and red light due to glowing particles. For the determination of the flame velocity, five BPW 34 silicon photodiodes 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 pre-detection 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.

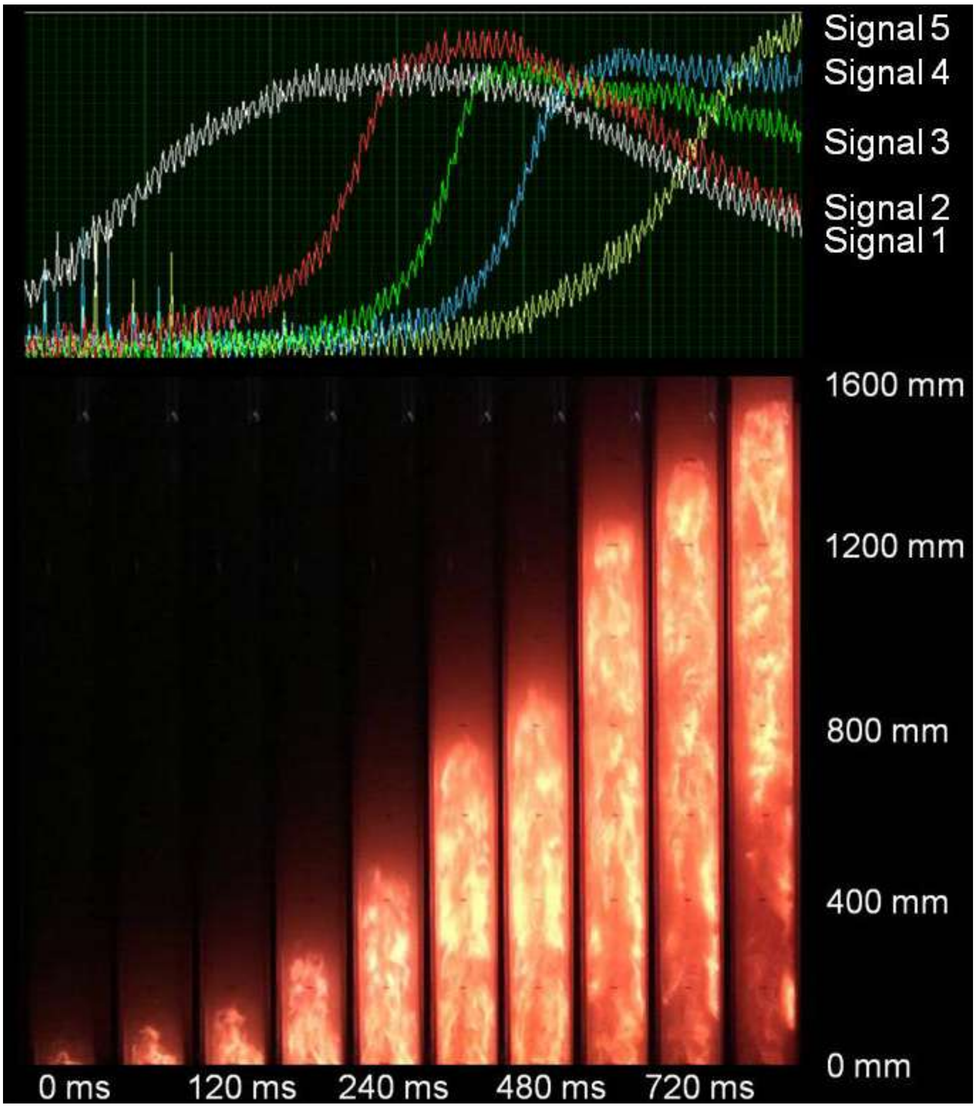

Figure 3: Signal development and flame propagation during an experiment with a dust concentration of 300 g/m³ at ambient pressure

Figure 3 describes the relation between the photodiode signals and actual flame propagation. The point 0 mm at 0 ms indicates the flame reaching the first photodiode. Around 240 ms later, the second diode at 400 mm is passed by the flame. Compared to the photodiode signals in the picture above, it can be seen that the signal peaks do not represent the exact location of the flame front.

It proved practical to measure the distances between defined offset points of the signal from the signal ground level. The offset point (POffset) was defined by the following equation (Eq. 1):

$$P_{offset} = Signal + 3\sigma_{signal} \qquad (1)$$

The variable σ_{signal} indicates the standard deviation of the signal. The flame velocity was then calculated (Eq. 2) out of the time interval between the offset points of the first and the second signal (Δt) and the distance between the photodiodes (Δs).

$$S_F = \frac{\Delta s}{\Delta t} \qquad (2)$$

For calculation of the flame speed only the signal of the first two photodiodes was used. First experiments during construction of the apparatus revealed that the flame undergoes a certain acceleration reaching velocities at the top of the apparatus differing from those in the first section of up to an order of magnitude. Stable values could only be obtained in the first section of the combustion tube.

The camera system was not used for the determination of the flame speed but only to be able to analyse the flame propagation process visually and to determine the flame shape.

Results and discussion

Flame Propagation

At ambient conditions the flame forms a parabolic shape due to wall effects [9]. During the experiments under reduced pressure conditions, a change in the appearance of the flame was noticed. The closed flame shape that is formed at ambient pressure becomes distorted during reduction of pressure (Figure 4). At the given concentration, flames at 450 mbar and 250 mbar show nearly the same flame speed of around 7 m/s but appear visually as completely different.

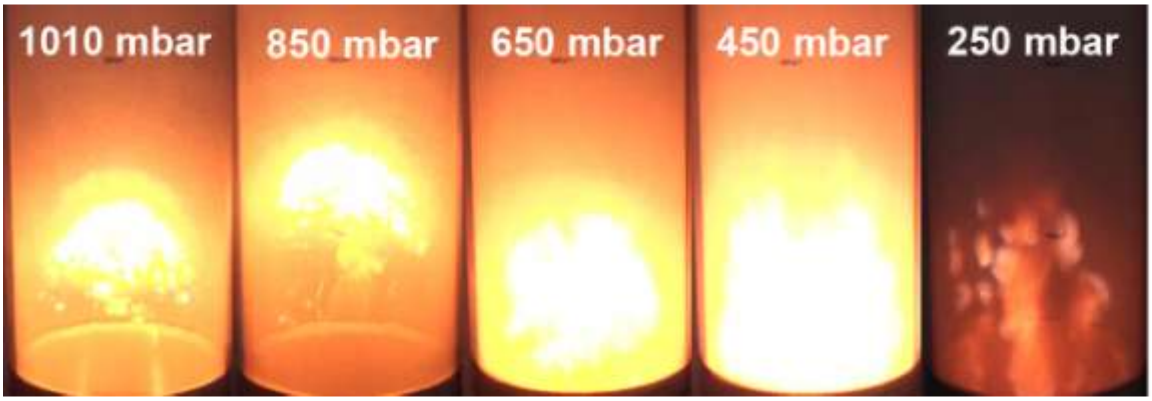

Figure 4: Development of the flame shape during the reduction of pressure (lycopodium/air at 100 g/m³)

At 250 mbar the flame does not form a uniform flame surface anymore and is dominated by single spot flames. In addition, the light intensity of the flames in the low pressure area is much lower than at ambient pressure, which may be caused by lower combustion temperatures.

Flame speed

Investigations on flame speed were conducted in the apparatus described in Figure 1. For igniting the dust/air mixture the spark generator described in 2.2 (IE ~10 mJ) was used.

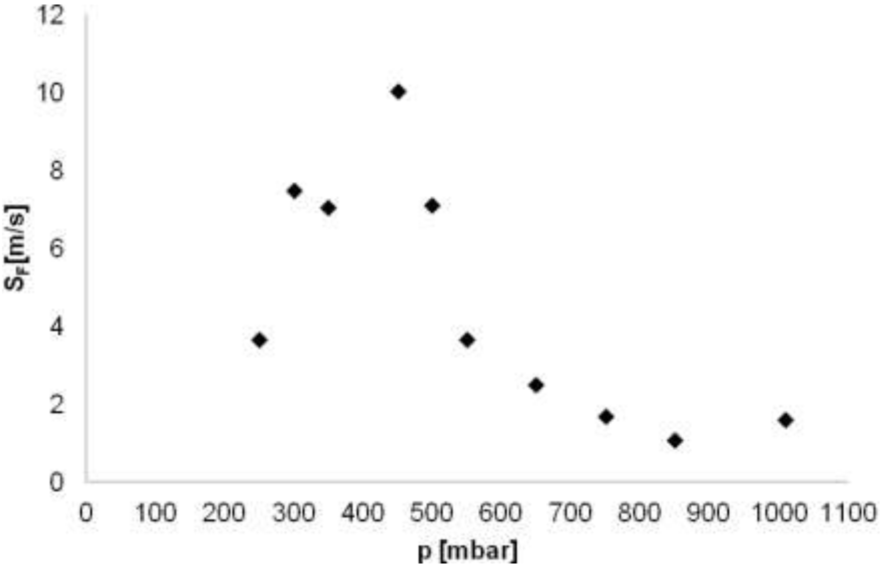

Figure 5: Pressure vs. flame average velocity at 100 g/m³ lycopodium

During the experiments the apparatus was evacuated down to the designated pressure level and ignited after around 30 s of dust feeding to assure homogeneous dust dispersion. Experiments on the settling behaviour showed a homogeneous dispersion of the dust approx. 50 cm below the feed point. The uniformity of the dust cloud was measured by two concentration sensors based on light extinction, 100 mm and 500 mm above the ignition point. CFD simulations on settling behaviour have been carried out and gave the same results regarding time and concentration profile. Experiments were carried out at dust concentrations of 100 g/m³, 200 g/m³ and 300 g/m³. Figure 5 shows the results of the first set of experiments carried out at 100 g/m³.

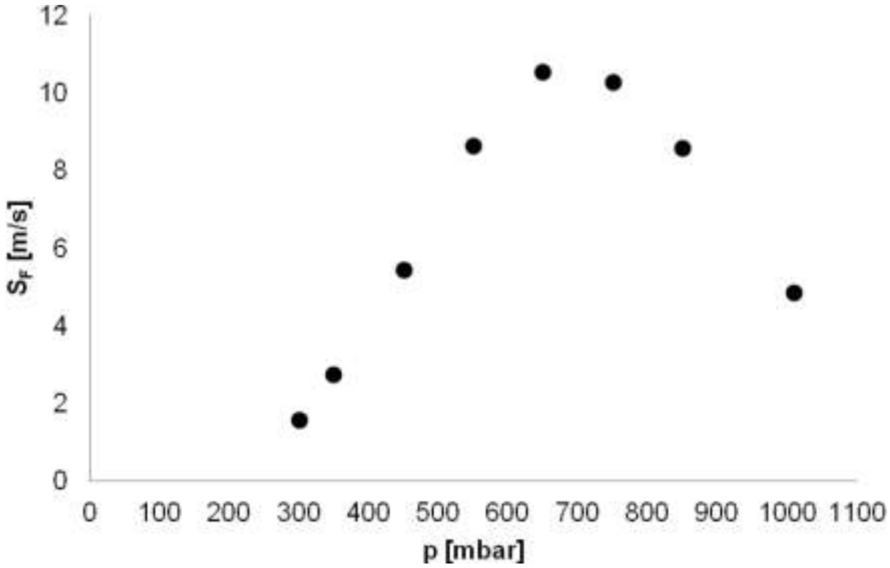

Figure 6: Pressure vs. average flame velocity at 200 g/m³ lycopodium

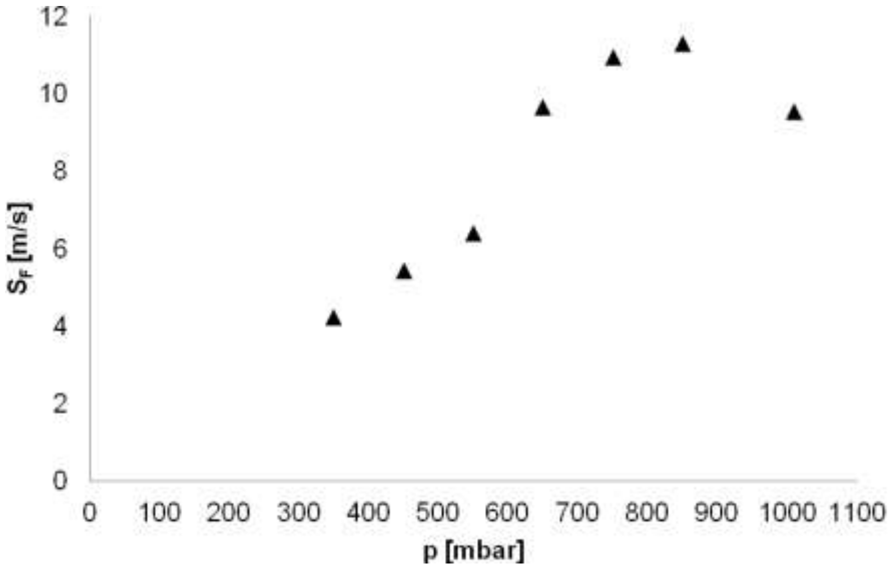

Figure 7: Pressure vs. average flame velocity at 300 g/m³ lycopodium

A relatively stable flame speed was found between 1010 mbar and 750 mbar. Below 750 mbar the flame speed increases significantly reaching a maximum at 450 mbar. Further reduction of the pressure slows down flame propagation. With the spark generator used, igniton below a pressure of 250 mbar was impossible. As described above, the formation of a parabolic flame shape was not observed at very low pressures. The considerably high flame speed and the not very bright flame also led to a stronger variation of the values measured at reduces pressures.

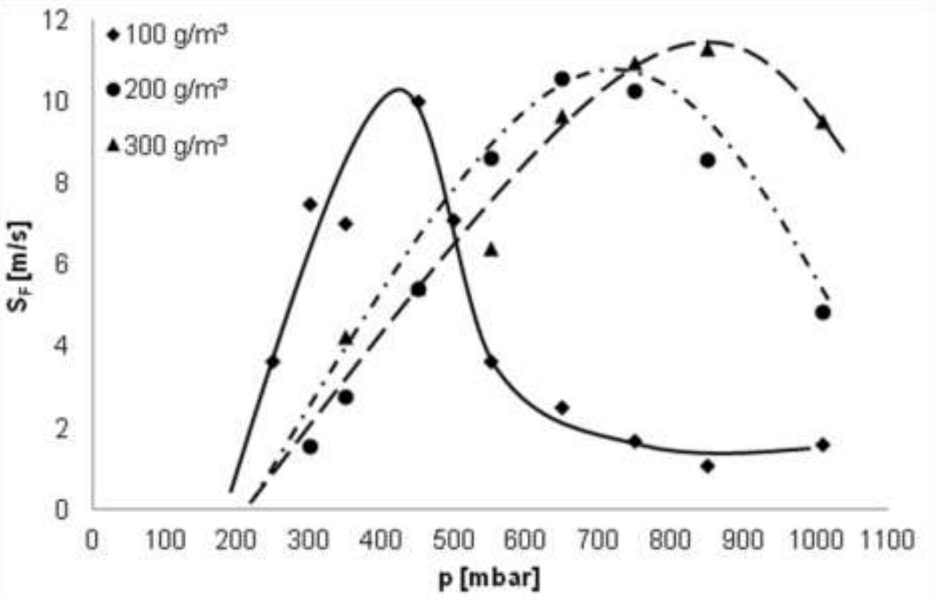

Figure 8: Pressure vs. average flame velocity at 100 g/m³, 200 g/m³ and 300 g/m³ lycopodium

Figure 6 demonstrates of the results the flame speeds measured at a concentration of 200 g/m³ lycopodium in air during the reduction of pressure. Corresponding to the previous set of experiments, the flame speed rises during the reduction of pressure. A section of constant flame speed was not found. Maximum flame speed was observed at around 650 mbar. Ignition became impossible at a pressure of 300 mbar. As can be seen in Figure 7, the maximum of the flame speed shifted further towards ambient pressure when the dust concentration was raised to 300 g/m³. The limit of ignitability shifted further and was reached at 350 mbar.

A comparison of all three datasets reveals that maximum flame velocities can be achieved at different pressures depending on the fuel concentration (Figure 8). The slope of the increasing as well als the decreasing flank of each curve also varies with the dust concentration. The curve at 100 g/m³ is more narrow than at the other two concentrations. The curves spread with increasing dust concentrations. Interestingly, the falling flanks of all three curves seem to join at a value of around 200 mbar when extrapolated. 1 m³ of air at 200 mbar contains the amount of oxygen that is necessary for the total combustion of 20-25 g of lycopodium. The lower explosion level of lycopodium lies right in this area. Therefore, the result seems consequent.

Conclusions

Flame velocity is not a very common parameter for the evaluation of combustible dust/air mixtures, but the experimental settings chosen in this work allowed investigations of flame spread under reduced pressure conditions. In contrast to present testing equipment, the equipment used for this study allowed a closer look at the combustion process itself. It was possible to investigate the influencing parameters on and the conditions at the ignition process in a more detailed way than possible with the 20 l Siwek chamber or the MIKE 3 apparatus.

The experiments below atmospheric conditions revealed effects that had not been predictable in the first place. Flame speeds generally increased during pressure reduction up to a certain peak value and decreased after passing that maximum speed. Flame speeds measured at low pressure conditions reached an order of magnitude higher than at ambient conditions for the investigated dust concentrations of 100 g/m³, 200 g/m³ and 300 g/m³. The velocity maximum shifted towards atmospheric pressure with increasing dust concentrations. Also the flame shape and appearance differs strongly from atmospheric conditions. Within the measurement and detection system there is still room for improvement but the results presented in this paper revealed some new perspectives in the research of flame propagation.

The results may not be applicable directly to a practical problem set but enable further research on the mechanisms and influencing parameters of the combustion process. From the knowledge thus gained, theories of combustion processes under atmospheric conditions can be improved.

References

[1] Kern, H., Explosible Dust/Air Mixtures - Investigations on flame propagation under non atmospheric conditions, PhD Thesis, Montanuniversität Leoben, Leoben, 2013.

[2] Wieser, G., Untersuchung der Flammenfortpflanzung in Staub/Luft-Gemischen unter reduzierten Druckbedingungen, Master Thesis, Montanuniversität Leoben, Leoben, 2013.

[3] Steen, H., Handbuch des Explosionsschutzes, WILEY-VCH, Weinheim, 2000.

[4] Proust, C., A few fundamental aspects about ignition and flame propagation in dust clouds, Journal of Loss Prevention in the Process Industries 19 (2006), 104–120.

[5] Han, O. S., Yashima, M., Matsuda, T., Matsui, H., Miyake, A., Ogawa, T., Behaviour of flames propagating trough lycopodium dust clouds in a vertical duct, Journal of Loss Prevention in the Process Industries 2000 (13), 449–457.

[6] Palmer, K. N., Tonkin, P. S., Coal dust explosions in a large-scale vertical tube apparatus, Combustion and Flame 1971, 17, 159–170.

[7] Kern, H., Held, K., Raupenstrauch, H., Investigations on the influence of the oxygen concentration on the flame propagation in lycopodium/air mixtures, ACHEMA Congress 2012, Frankfurt 2012

[8] Bartknecht, W., Zwahlen, G., Explosionsschutz, Springer, Berlin [etc.], op. 1993.

[9] Eckhoff, R. K., Dust explosions in the process industries, Butterworth-Heinemann, Oxford [u.a.], 1997.