Measurements of the laminar burning velocities in dust-air mixtures

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1 INTRODUCTION

Dust explosion propagation is dominated by two parameters: turbulence and a basic reaction velocity. The first parameter describes the fluid dynamic conditions of the reactive mixture at the moment it is consumed by the flame. The second parameter describes the velocity of the reaction front through a stagnant mixture of dust particles and air. This reaction velocity is the velocity resulting from a scala of processes such as heat transport in the dust particles, diffusion of oxygen into the dust particles, heat radiation between the particles and diffusion of radicals and heat from particle to particle.

Although dust explosions have been threatening mankind during a long time now no attempts were made until recently to try to discriminate between the two parameters. Tests to determine dust explosion propagation properties normally are performed with a certain level of turbulence prevailing in the mixture. The most important dust explosion propagation parameter which is determined in this respect is the K_{st}-value [1].

The K_{St}-value cannot be considered as a basic parameter because of the presence of turbulence in the mixture. Dusts which have similar K_{St}-value were found to behave very differently in identical test situations. Such circumstances were mainly related to circumstances where the flame is generating turbulence itself. Such situations occur e.g. when the dust explosion is propagating through a pipe [1] or in integrated system [2]. The expansion flow generated by the expanding combustion products causes turbulence in the unburned dust-air mixture ahead of the flame at solid walls and/ or obstacles. The turbulence will cause an increase of the burning rate and an increase of the expansion flow. More intense turbulence is generated at the walls and/or obstacles etc. Some dusts appear to give rise to unexpectedly high pressures when exposed to such situations whereas other dusts with similar K_{st}-values generate moderate pressures only. This could certainly lead to dangerous situations. Hence it is important to have basic properties describing the reaction velocity in stagnant mixtures and tools to describe the effect of turbulence on the propagation of the dust flame. The latter would be in the form of a CFD-tool provided with an adequate combustion model allowing for describing the effects of turbulence (scale and intensity) on the combustion rate using the basic reaction velocity as a fundamental property.

In this article the results of an investigation are described aiming at measuring such a fundamental reaction velocity for dust-air mixtures. This reaction velocity is most often referred to as laminar burning velocity.

2 EXPERIMENTAL EQUIPMENT AND PROCEDURE

To measure to laminar burning velocity a 1.6 m long vertical tube made of transparent polycarbonate is used. The inner diameter of the tube was 0.128m. Dust was supplied continuously into the top of the tube from a horizontally vibrating sieve and a vibratory dust feeder. Two guillotine valves (slide valves) which were driven by compressed air were installed at the top and bottom of the tube. The top valve was a solid plate which closed the top of the tube when it was in its extended position and similarly the lower valve closed the bottom of the tube, except for a 32mm hole in the centre of the slide plate. The ignition point was located 0.123m from the bottom valve in the open end of the tube. Ignition was effected by an inductive electric spark. The dust concentration was measured using the principle of light attenuation by the presence of dust particles by fibre optic probes (infrared light) located 0.20m above the ignition point (calibrated in dust/decanol mixtures). A piezoelectric pressure transducer was mounted 0.40m from the top of the tube allowing for recording of pressure development during an explosion.

All the experiments were recorded using a Panasonic Super-VHS video system which had a capability of 50 frames per second. The flame front velocity was estimated from the video recordings.

The vertical tube is shown schematically in Figure 1.

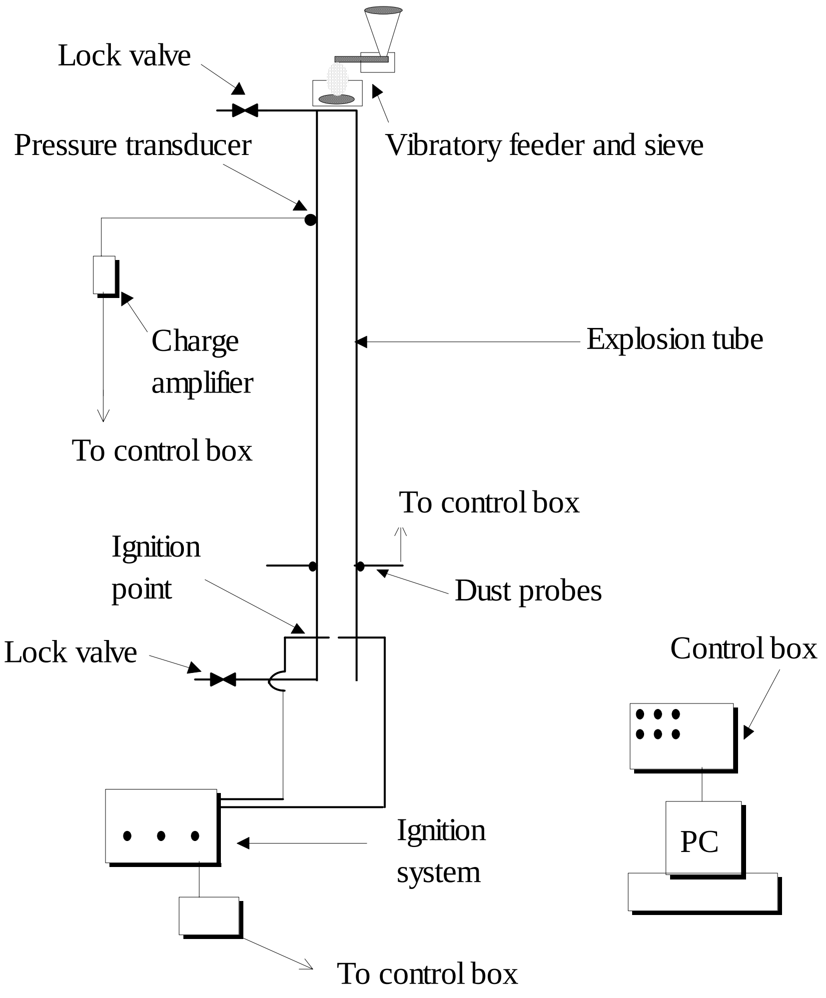


Figure 1 Schematic figure showing the apparatus used in the experiments.

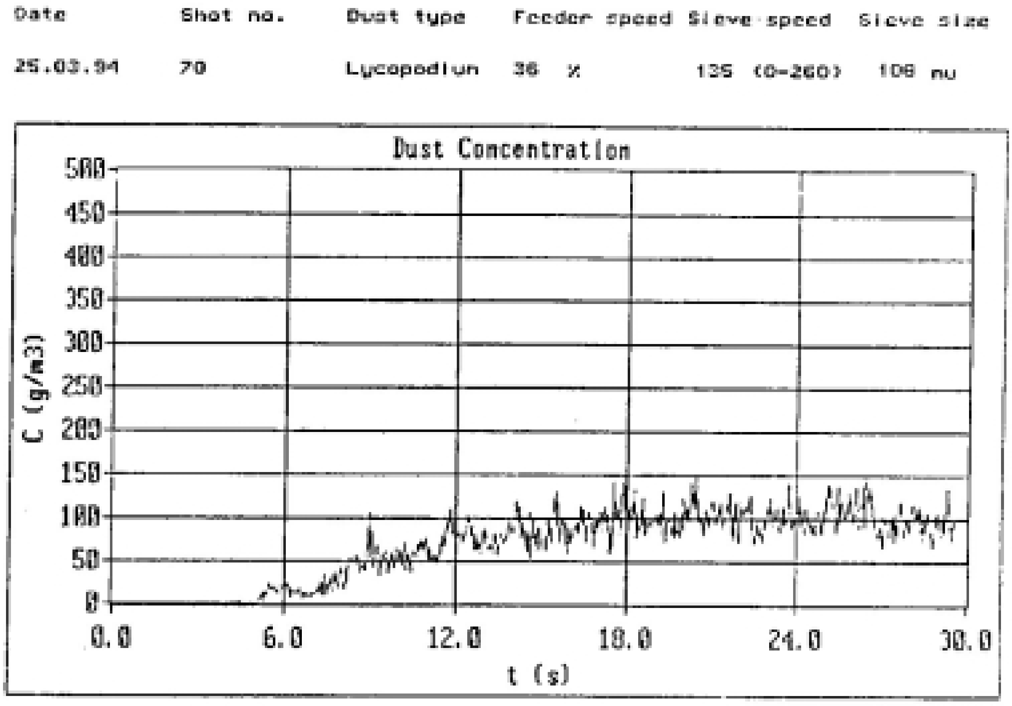
The laminar burning velocity was measured for five different dusts over a wide range of dust concentrations: lycopodium, Sirona cornstarch, maize starch, lignite dust and hard coal.

The flame front velocity was estimated from video recordings. The distance travelled by the flame as it progressed away from the ignition point was measured from the video recordings which yielded flame front contours at 0.02 s time intervals. To estimate the flame velocity basic distance over time calculations were made. In order to obtain the laminar burning velocity from the flame front velocity the method proposed by [3] was applied. The laminar burning velocity may be written as follows:

$$S_L = \frac{A}{A_f} \cdot S_f$$

where S_L is the laminar burning velocity, S_f the flame velocity, A_f the surface of the flame zone and A is the cross section of the tube. It is assumed that S_L is constant over the entire cross section of the tube and that the flame velocity is uniform over the tube cross section. The ratio A/A_f was obtained from video recordings. The error in the calculated laminar burning velocity was estimated to be approximately 0.02 m/s.

The dust concentration records showed a variation in dust concentration during the dispersion period and therefore the exact dust concentration in the tube was difficult to confirm. In order to obtain the dust concentration in the tube an average of the concentration probe output, just prior to ignition, was used. A typical record of the dust concentration obtained from a test of lycopodium/air is shown in Figure 2. The error in the calculated dust concentration was estimated to be approximately 20 g/m^3.



Date	Shot no.	Dust type	Feeder speed	Sieve speed	Sieve size
25.03.94	70	Lycopodium	36 %	135 (0-260)	108 mu

Figure 2 A typical record showing the dust concentration as a function of time.

3 PROPERTIES OF INVESTIGATED DUSTS

Six different dusts were investigated and some properties of the dust were determined. Moisture content in the dust was measured as well as the particle size distribution. The maximum explosion pressure, P_{max}, and $(dP/dt)_{max}$ and K_{max} were investigated in a 20 litre sphere.

Table 1 Moisture content for four of the five dusts investigated.

Dust type	**Moisture content (%)**
Lignite dust	17
Sirona cornstarch	12.5
Maize starch	10.8
Hard coal	0.9

The particle size distributions were determined by dry sieving.

Table 2 Measured particle size distribution for four of the five dusts investigated.

Dust type	**% > 32 µm**	**% > 45 µm**	**% > 63 µm**	**% > 75 µm**	**% > 106 µm**	**% > 125 µm**
Lignite dust	100	98.4	-	73	-	23.1
Sirona cornstarch	82.5	68	46	-	5	0.1
Maize starch	78	67.5	35.9	-	5.85	-
Hard coal	100	95.8	-	70.5	-	25.7

Lycopodium is an almost monodisperse material and the mean particle size is about 30 µm.

Each dust was also tested in the 20 litre sphere and the results are shown in the following table.

Table 3 Results from the 20 litre test for the investigated dusts.

Dust type	**P_{max} (bar)**	**$(dP/dt)_{max}$ (bar/s)**	**$K_{max} = K_{st}$ (m*bar/s)**
Lycopodium	6.7	474	129
Lignite dust	8.6	691	188
Sirona cornstarch (dried)	6.9	645	175
Maize starch (dried)	7.6	593	161
Hard coal	8.1	533	145

4 RESULTS

4.1 Visual observations

During the dust dispersion period it was observed that the dust particles in the tube fell at a higher velocity than expected considering the particle size distribution. This indicates agglomeration of dust particles. Shadowgraphy reveiled inhomogeneities of the dust cloud.

The flame fronts usually exhibited a characteristic parabolic shape, but the flame fronts were not as smooth as observed for flame fronts in gas-air mixtures. The dust flame fronts were thicker than a gas flame front. Along the tube wall quenching occurred up to a distance of approximately 1-2 cm from the wall. As the flame front propagated through the tube a strong afterburning was observed. This afterburning exhibited itself as burning pockets seperated by non-burning areas. Despite this the flame velocities evaluated were relatively constant. Some of the dust flames were strongly luminous with a diffuse flame front. These flames were several cm thick. Such luminous flames were observed at higher dust concentrations and the speed of flame propagation was high as well. In the low and middle dust concentration range a more stable flame propagation was observed.

4.2 Results of laminar burning velocity measurements

The laminar burning velocity as a function of dust concentration for the dusts that were investigated are shown in the Figures 3-6. The burning velocities presented are those obtained after correction for the flame surface area as described above. The flame surface area correction did not take small cells causing addtional flame folding into account.

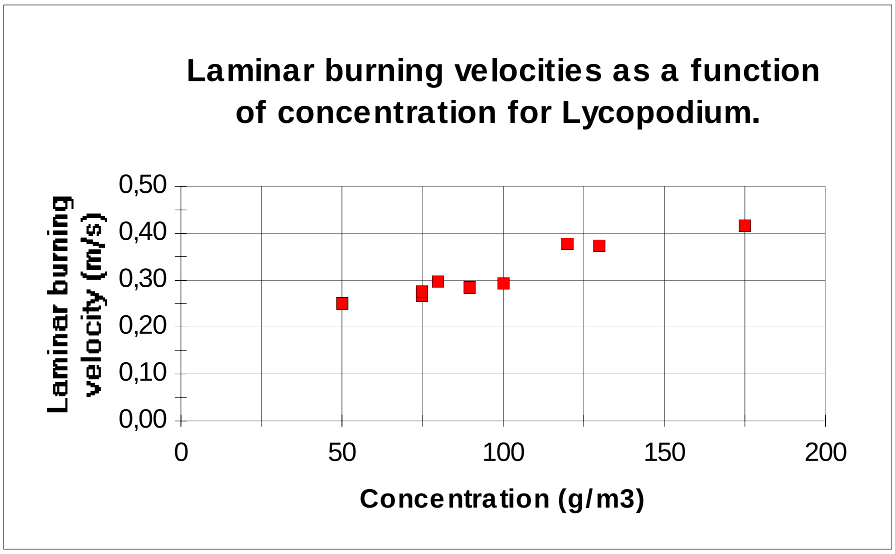


Figure 3 Laminar burning velocity measured as a function of dust concentration for Lycopodium.

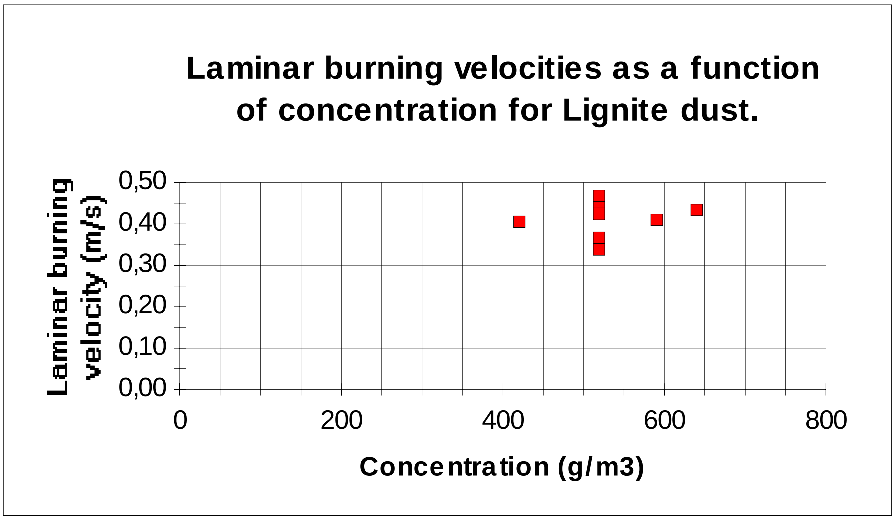


Figure 4 Laminar burning velocity measured as a function of dust concentration for Lignite dust.

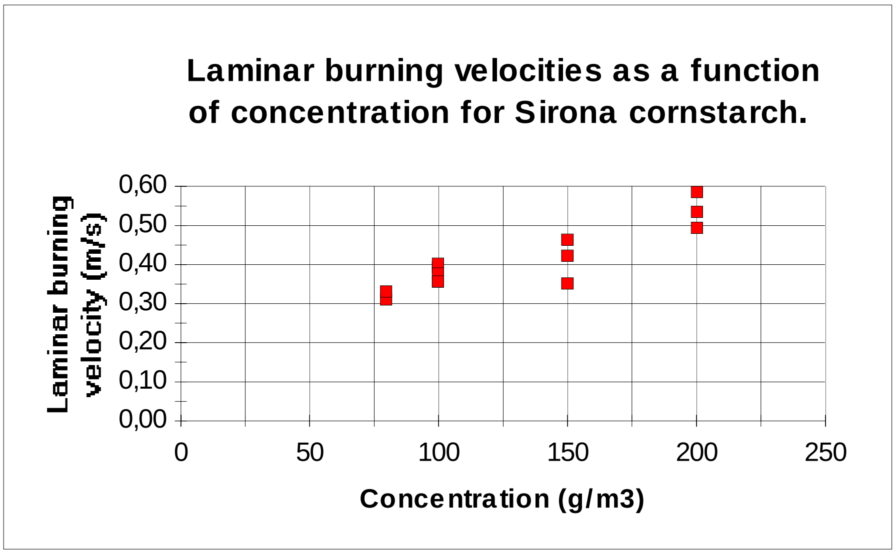


Figure 5 Laminar burning velocity measured as a function of dust concentration for Sirona cornstarch.

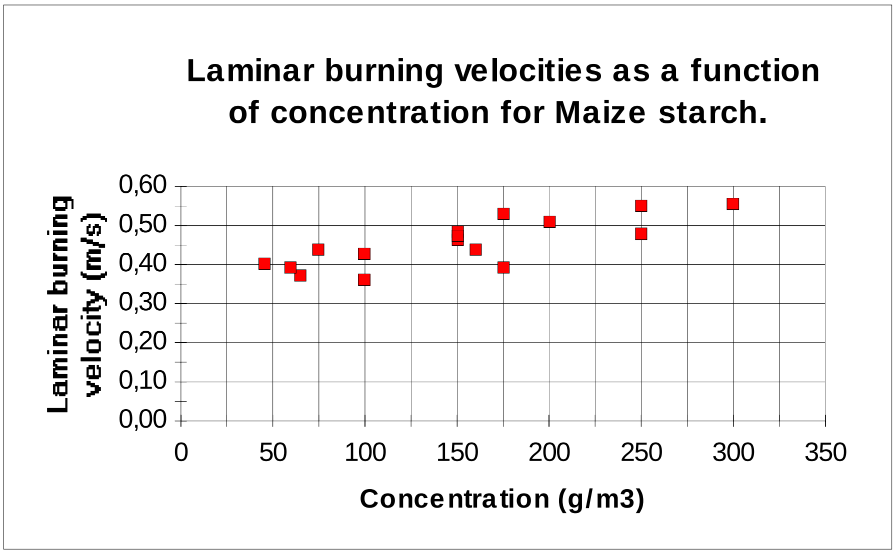


Figure 6 Laminar burning velocity measured as a function of dust concentration for Maize starch.

The hard coal could not be ignited and therefore no laminar burning velocities could be measured.

5 DISCUSSION

It appeared that for none of the dusts that were investigated a maximum laminar burning velocity could be observed. It was not possible to prepare mixtures with a higher concentrations using the present dust dispersion system.

The scattering of the data may be caused by the difficulties experienced in obtaining repeatability in the experiments and in the accuracy of the control of the dust concentration.

The laminar burning velocities that were obtained and presented above are probably affected by the fact that the dust was agglomerated. The after burning is probably related to these agglomerations.

Further it was observed that due to dust dispersion, turbulence was generated in the tube. Using Laser Doppler Anemometry turbulence measurements were performed revealing some large-scale vortex structures in the tube. Velocity fluctuations of up to +/- 0.4 m/s were observed. It is expected that this turbulence will have affected the measurements as well. The cellular flame structure that was observed may be related to this turbulence. The turbulence may be caused by turbulence in the wake of particles or it may be large-scale turbulence related to the bulk flow in the tube due to the dust falling in. When considering turbulence in the wake of particles it should be mentioned that according to [4] vortex shedding in the wake of particles first arises at Reynolds numbers of 20 or higher. Actual turbulence does not occur until Reynolds numbers of Re=400-500 [5]. Only very large particles will when considering their settling velocity generate vortices (> 500 μm). A higher initial velocity is necessary to generate actual turbulence. Since the scale of this turbulence if it would have been possible to generate is related to the size of the particles the scale would be in the order of 10-50 μm. This would imply a very fast dissipation and hence decay [6]. The turbulence in the tube does not decay that fast which indicates that the scale of turbulence is related to the size of the tube. Hence one can conclude that the turbulence generated in the tube is due to a bulk flow resulting from the injection of dust from the top of the tube.

It is noted that the present measurements reveal laminar burning velocities for the investigated dusts which are in the same order of magnitude as those of common hydrocarbons such as methane (S_L = 0.43 m/s) and propane (S_L = 0.46 m/s).

As expected there is a relationship between the K-value and laminar burning velocity for the different dusts investigated. Figure 7 presents this relationship for three of the investigated dusts. The Figure does not allow for drawing any definitive conclusions with respect to a single relationship between the two parameters but it is clear that an increase of the laminar burning velocity results in an increase of the K-value of each of the dusts. The relative difference between the maize and corn starch as a group (these two dusts are very much alike) and lycopodium may be due to the uncertainties in the measurement of the laminar burning velocity as well as the relative difference of the effect of turbulence on the combustion of the dusts.

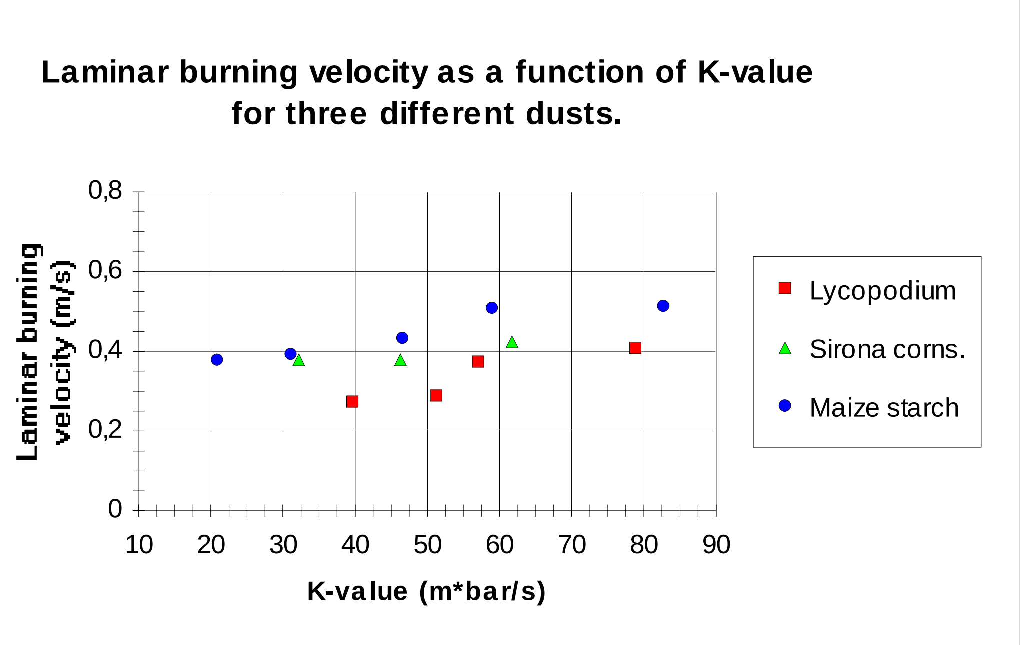


Figure 7 A plot showing the relationship between laminar burning velocity and K-value for different dust concentrations for three dusts investigated.

Although several authors have been reporting laminar burning velocities of dust-air mixtures a direct comparison of results is possible for only a few studies. The main reason for this is differences in the concentration range that was used in the experiments. For those studies where a direct comparison is possible an overview is presented in Table 4.

The table shows a reasonable agreement for lycopodium but clearly higher values are found for corn starch and maize starch in the present study. A reason for this difference may be the way of dust cloud generation resulting in turbulence. The other studies mentioned in the table use a fluidised bed technique for generating dust clouds. This observation may mean that a relationship between the laminar burning and K-value (Figure 7) does exist.

Table 4 Comparison of laminar burning velocities and method of measurement given in literature.

Reference	**Method**	**Concentration (g/m^3)**	**Laminar burning velocity (m/s)**
Lycopodium			
Proust [7]	Tube 10 cm x 10 cm square	35-80	0.25-0.47
Present work	Tube of 12.8 cm in inner diameter	60-175	0.23-0.41
Corn starch			
Krause and Kasch [8]	Tube of 10 cm in diameter	80-430	0.20-0.30
Present work	Tube of 12.8 cm in inner diameter	80-200	0.31-0.59
Maize starch			
Proust and Veyssiere [9]	Tube 20 cm x 20 cm square	75-275	0.2-0.3
Proust [7]	Tube 10 cm x 10 cm square	80-280	0.12-0.22
Present work	Tube of 12.8 cm in inner diameter	45-300	0.36-0.55

6 CONCLUSIONS

Laminar burning velocities have been measured for five different dusts (lycopodium, corn starch, maize starch, lignite dust and hard coal). One dust could not be ignited (hard coal). The measured values for the other four dusts have been summarized in Table 5.

Table 5 Summary of the laminar burning velocity measurements.

Dust type	**Concentration in air (g/m^3)**	**Laminar burning velocity (m/s)**
Lycopodium	60-175	0.23-0.41
Corn starch	80-200	0.31-0.59
Maize starch	45-300	0.36-0.55
Lignite dust	420-640	0.34-0.47
Hard coal	-	-

7 ACKNOWLEDGEMENT

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