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# Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 $m^3$ Dust Explosion Method

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The ISO 1 $m^3$ dust explosion vessel was instrumented with thermocouples acting as flame detectors. These were used with methane/air gas explosions to show that the explosion flame was spherical in the constant pressure phase of the explosion and that a reliable flame speed and burning velocity could be obtained. This technique was used to determine the turbulent burning velocity using the same method of compressed air injection as used in the ISO 1 $m^3$ dust explosion tests. This enabled the mean turbulent flame enhancement factor of the air injection system used in the ISO 1$m^3$ equipment to be determined as 4.0. The mean flame speed was measured for dusts and these were shown to correlate linearly with the $K_{st}$ for that dust. The turbulence factor determined from gas explosions was used to derive the laminar flame speed for the dusts and then using the adiabatic constant pressure expansion ratio the laminar burning velocity was derived. This gave peak laminar burning velocities in the 0.15 – 0.55 m/s range for the dusts investigated: corn flour, lycopodium, walnut, Kellingley coal, pistachio nuts. These were in good agreement with other measurements in the literature.

## 1. Introduction

Modelling of gas and dust explosions requires knowledge of the laminar burning velocity, $S_L$, which is a major area of research for gas flames. For dust flames there is no agreed methodology for its measurement and hence no agreed values that can be used in explosion protection design standards. Andrews and Bradley (1972) showed that there were systematic errors in most methods of determining the laminar burning velocity and these were related to the finite thickness of the flame preheat and reaction zone and the assumption of an infinitely thin flame in many of the measurement methods. Some recommended values of burning velocity for measurement methods with low errors were recommended by Andrews and Bradley (1972) and adopted by NFPA (2013). The problem of the lack of a standard for laminar burning velocity gas flame reactivity measurements were side stepped by NFPA (2013) by specifying a reference value for the maximum reactivity mixture of propane/air as 0.45 m/s and any other measurement for other gases had to be referenced to this using the value that that method gave for propane. For dusts no data base exists for laminar burning velocities, as few measurement methods exist, due to the need for turbulence to keep the dusts in suspension. Measurements of the laminar burning velocity of dusts are rare due to the continued use of $K_{st} = dP/dt_{max}/V^{1/3}$ as the reactivity or deflagration index for dusts, rather than the burning velocity. This is a turbulent flame measurement at the arbitrary turbulence generated in the ISO 1 $m^3$ dust explosion method.

In venting research for gases the deflagration index, $K_G = dP/dt_{max}/V^{1/3}$, is used in the European gas vent design standards (2007) and this used to be used in the USA vent design standards for gas explosions, but has recently been replaced with the use of $S_L$. (NFPA, 2013). NFPA (2007) used to recommend values for $K_G$ taken from Bartknecht (1993) who used explosion measurements in a 5L sphere and the European standards still recommend this method (2011). It is thus surprising that for dust explosions, methods were agreed nearly 30 years ago on how $K_{st}$ should be measured (ISO, 1985) and this requires the use of a 1 $m^3$ explosion vessel. The present work shows that this vessel can also be used to accurately determine the flame speed, $S_F$, and burning velocity, $S_L$, of laminar gas/air mixtures, which enables the mean turbulence

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in the ISO dust explosion vessel to be determined. It is also recommended that better values of $K_G$ are measured in this equipment than in a 5L sphere.
Phylaktou et al. (2010) showed that turbulent flame speeds $(S_F)_T$ could be measured in the constant pressure period of dust explosions in the ISO (1985) 1 $m^3$ dust explosion vessel using an array of exposed junction thermocouples as flame arrival detectors. They attempted to measure the laminar flame speed by increasing the ignition delay between the start of dust and compressed air injection and the firing of the ignitor. The reference time delay is 0.6s after the start of air flowing into the vessel (Bartknecht, 1993), which was determined from the rise in pressure of the pressure transducer in the 1 $m^3$ vessel. The ignition delay was increased in stages up to 4s delay, by which time the injection turbulence had decayed to laminar conditions. Unfortunately in most cases, before laminar conditions had been achieved the peak overpressure started to fall, indicating that significant proportions of the dust injected had fallen out under gravity. This then results in low accuracy estimations of the laminar flame speed based on extrapolation from flames speeds as a function of the ignition delay, ignoring data where there was evidence of loss of dust by deposition (Phylaktou et al., 2010). The present work aimed to determine the mean turbulence levels in the ISO 1$m^3$ dust explosion method using laminar and turbulent methane/air explosions to determine the turbulence enhancement factor and then apply this to the measured turbulent dust/air flame speeds to determine the laminar flame speed.
The most common other method of burning velocity measurements is to use the vertical tube method with dust falling from the top and ignition at the bottom. Proust and Veyssiere (1988) showed that laminar flames could be achieved, but Andrews and Bradley (1972) showed that this method did not give reliable values of burning velocity for gas/air mixtures and the same is likely for dusts/air explosions. Improvements to the method were made by using the dust particle motion ahead of the flame to determine the gas velocity ahead of the flame, so that the burning velocity was the difference between the flame speed up the tube and the gas velocity ahead of the flame (Wolanski, 1995; Proust, 1993). The results from this method showed considerable data scatter of the order of +/-100% and hence did not demonstrate a methodology that could be relied on for dust explosion reactivity characterisation. Also this work showed a very poor correlation between the $K_{st}$ and burning velocity reactivity parameters, when there can be shown to be a linear correlation between the two (Andrews and Phyaktou, 2010), which will be demonstrated in the present work.

## 2. Experimental Procedures

Dust and gas air mixtures were exploded in a 1.138 $m^3$ closed vessel constructed to the specifications of ISO 6184/1 (1985) for the determination of $K_{st}$. For dust explosions a measured mass of dust was placed in a 4.5L external pressure vessel pressurised to 20 bar with air, connected to a perforated C ring inside the vessel, via a fast acting pneumatic ball valve. The main vessel was pumped down to 923 mbar(a) pressure and addition of the compressed air and dust raised the pressure to a standard atmosphere. The ignition source for dusts was two 5kJ chemical ignitors directed against a small hemispherical cap to produce a spherical ball of hot gases that resulted in spherical flame propagation. The standard ISO method has directional effects from the ignitors and does not have spherical flames. The proof that spherical flames had been achieved was from the flame speed measurements in at least two planes at 90$^o$. For gas explosions the gas mixture was made up by evacuating the vessel and adding the gas in a concentration determined by partial pressure. The gas and initial air was at 923mbar(a) and the same air addition from the external pot was used with the same delay of 0.6s between the initiation of the flow of compressed air and the ignition. This was aimed at achieving the same turbulence with gas as with the dust explosions. For gases laminar flames could be achieved simply by making a mixture up by partial pressure with all the vessel full of air initially at a standard atmosphere. For gases the spark was a 16J electrical spark for laminar and turbulent mixtures.
For both gas and dust explosions the flame speed was determined by the time of arrival of flames at an array of exposed junction Type K mineral insulated thermocouples. These were located in three planes at 90$^o$ to each other so that spherical flame propagation could be demonstrated. The location of the thermocouples relative to the pressure rise in a 10% methane-air explosion is shown in Figure 1. The aim was to measure the flame speed in the constant pressure period of the explosion and Figure 1 shows that for flame diameters up to 800mm the pressure rise was <1%. When the flame was close to the spark at flame diameters <200mm the flame speed was influence by the flame curvature and for dust explosions it was influence by the initial ball of hot chemical ignitor products. For gases the flame speed was lower for small flame diameters, due to flame curvature effects as shown by Taylor and Smith (1995). They found for stoichiometric propane air mixtures in a 0.5m diameter spherical vessel, that the flame speed increased from 1.5 to 2.9 m/s over flame diameters 10 to 70mm and an equilibrium flame speed had not been

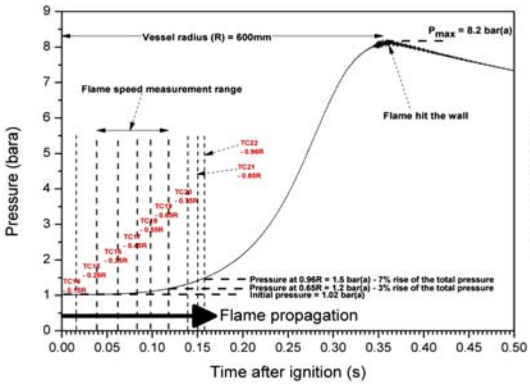


*Figure 1: Laminar 10% methane explosion pressure-time trace along with the time of flame arrival at vertical downward thermocouples and pressure rise.*

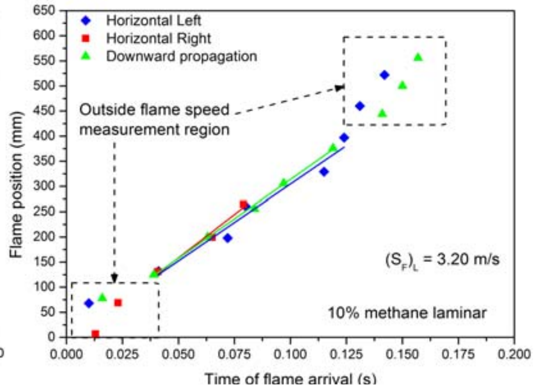


*Figure 2. Flame position versus time for 10% laminar methane test from this study. The flame position versus time outside the flame measurement region is also indicated.*

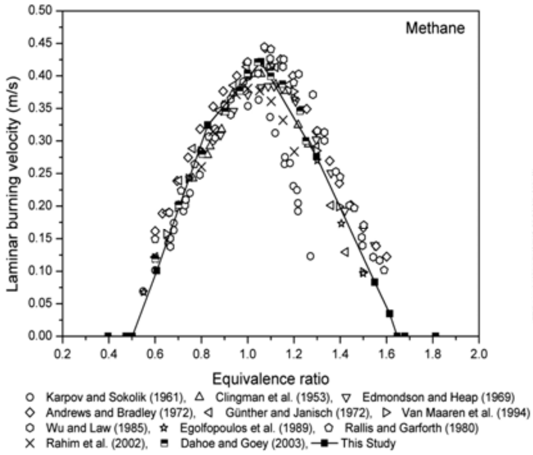


*Figure 3. Effect of methane equivalence ratio on the laminar burning velocity of methane/air as a function of equivalence ratio. Comparison of the present .measurements with previous measurements.*

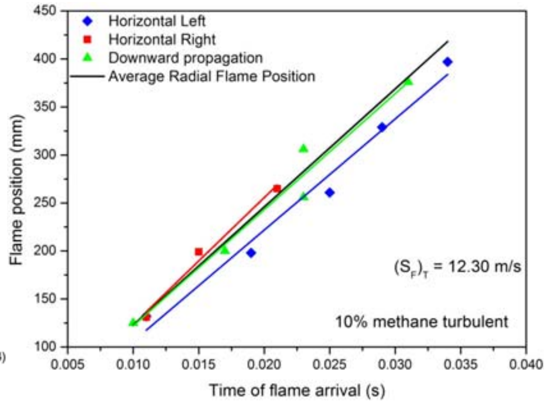


*Figure 4: Flame position versus time for 10% turbulent methane test from this studv.*

reached at 70 mm diameter. Thus it is reasonable in the present work that a 200mm diameter flame is taken as free of ignition and flame curvature effects. Beyond flame diameters of 800mm the rise in pressure and temperature due to compression would influence the flame speed. Also flame instabilities lead to cellular flames that cause flame acceleration if the flame diameter is large enough. The approach of Chippett (1984), adopted in NFPA68 (2013), for methane predicts at a flame diameter up to 800mm the flame self-acceleration will be <10%. For these reasons the flame speed was determined from the flame arrival times at thermocouples positioned between 200 and 800mm diameter. The flame arrival time results are shown in Figure 2, which includes all the thermocouple arrival times to show that the flame speed is non-linear if thermocouples at radii <100m of >400mm were included. Figure 2 shows that all three thermocouple arrays were reasonably parallel, demonstrating that a spherical flame had been achieved.

This flame is sufficiently large in diameter for the assumption of an infinitely thin flame front to be valid. The flame thickness of a stoichiometric laminar methane/air flame is about 1mm (Andrews and Bradley, 1972) and for the volume of the flame in the flame thickness to be <1% of the spherical volume the flame diameter has to be >600mm. Thus a 1m$^3$ spherical vessel is the minimum size for the flame thickness and related curvature effects to be small and hence not influence the flame speed measurement. This enables the laminar burning velocity, $S_L$, to be determined from the laminar flame speed, $(S_F)_L$ by dividing it by the adiabatic burned to unburned gas density ratio. Other users of this technique have used vessels that were

too small for the assumptions of the method to be valid and errors were of the order of 20% below the correct value of the burning velocity (Andrews and Bradley, 1972).
The present results for the laminar burning velocity of methane-air as a function of equivalence ratio are shown in Figure 3, which shows good agreement with other measurement techniques with low systematic errors. The work of Karpov and Sokolik (1961) in Figure 3 is typical of the use of small explosion vessels which give low values of $S_L$, due to the use of an explosion vessel that is too small at 150mm diameter. Their peak $S_L$ was 0.37 m/s, compared with 0.42 m/s in the present work. The good agreement with other methods in Figure 3 shows that the present laminar flame speed and burning velocity measurements are reliable and hence can be applied to turbulent gas flames and dust explosions.

## 3. Turbulent Gas/Air Flame Speed and Turbulent Dust Explosion Flame Speed Results

Figure 4 shows the flame arrival time results at the thermocouples for a turbulent 10% methane-air explosion, at the turbulence level used in the ISO 1 $m^3$ dust explosion methodology. The data scatter is greater than for the laminar explosions due to the random turbulent fluctuations at the flame front. However, a reasonable straight line relationship is shown, which demonstrates that the flame propagation was approximately spherical The flame speed in Figure 4 was 12.30 m/s, which is one of three repeat measurements and the average flame speed for the repeat tests was 12.8 m/s. The turbulent to laminar flame speed ratio (12.8/3.2) gives the turbulence factor, β, in the ISO air injection method as 4.0. It was also shown in this work that the ratio of turbulent to laminar $K_G$ was also β = 4.0 and this indicates that the turbulence was relatively uniform throughout the vessel, as the flame speeds are measured in the flame propagation in the central region of the vessel before the pressure starts to rise and $K_G$ is measured in the near wall region of flame propagation close to peak pressure, as shown in Figure 1. Gardner et al. (2001) showed that the work of Scheurmann (1994) for the mean turbulence in the ISO 1$m^3$ dust explosion vessel could be used with turbulent burning velocity correlations to predict a turbulent flame speed enhancement of 4, in agreement with the present results. This turbulence factor of β = 4.0 will be used to convert turbulent dust-air flame speeds to laminar flame speeds.

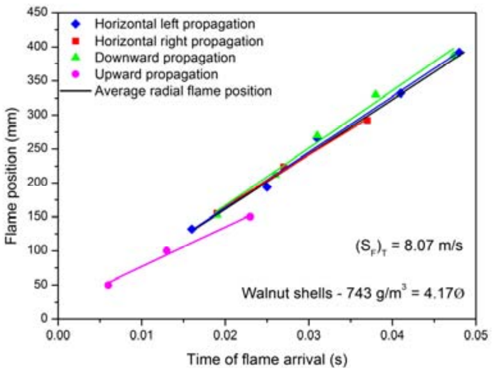


*Figure 5: Flame position versus time for most reactive of walnut shells. The slope of each line is the average flame speed in that direction.*

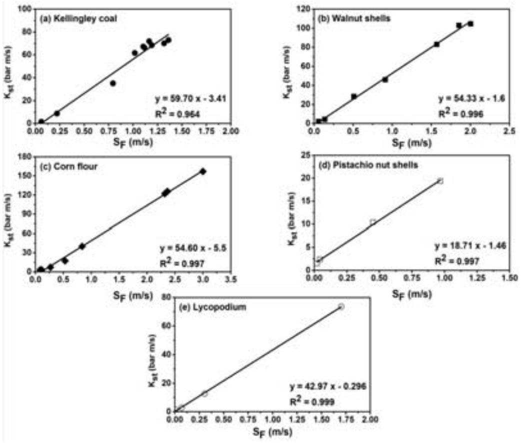


*Figure 6. Correlation of measured turbulent flame speeds and $K_{st}$ for Kellingley coal, walnut shells, cornflour, pistachio nut shells and lycopodium for the range of concentrations in Figure 7.*

Figure 5 shows a typical dust explosion flame speed measurement with good linear lines for three thermocouple arrays. The extra thermocouples shown here for upward propagation were fitted to help in the determination of the lean flammability limit and were closer to the spark than desirable for the flame speed measurements. For gas explosion lean flammability determination the European standard (2003) uses a minimum flame propagation distance of 100mm for the mixture to be flammable and so thermocouples around this location were used. Six repeat tests on dust explosions were carried out for corn flour at 750 g/$m^3$ concentration (based on the mass of dust added to the external pot), which is the concentration that has been found to be most reactive (Eckhoff, 2003) and these showed a mean value of $K_{st}$ of 157 bar/ms with a standard deviation of 5.8% and a 95% confidence interval of 149 – 175 bar/ms. Published values for corn flour range from 158 – 160 for 20L spherical vessels (Eckhoff, 2003; Skjold et al.,

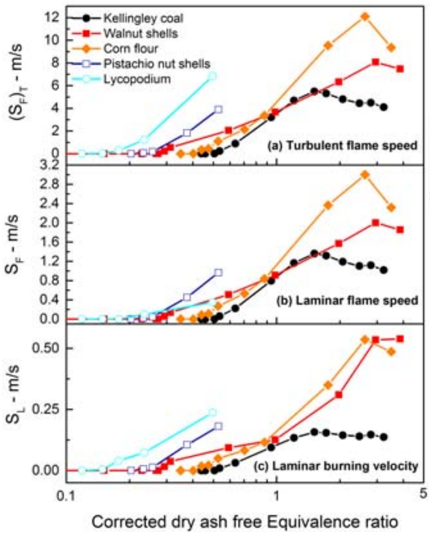


*Figure 7. Comparison of **(a)** measured turbulent flame speeds **(b)** laminar flame speeds from turbulent flame speeds using turbulence factor (β) and **(c)** laminar burning velocities derived from laminar flame speed using constant pressure expansion ratio for Kellingley coal, walnut shells, cornflour, pistachio nut shells and lycopodium against dry ash free corrected equivalence ratio.*

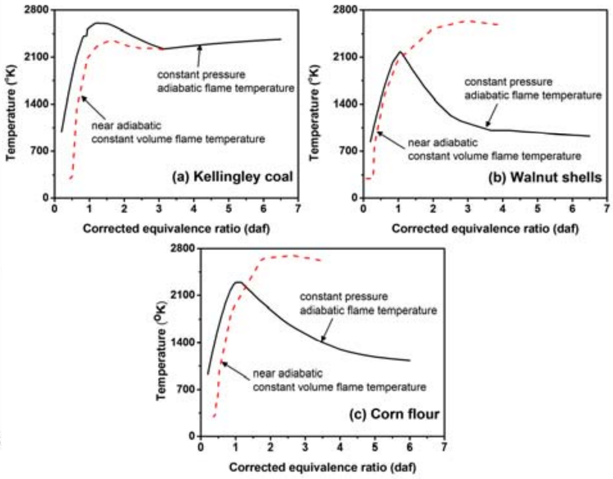


*Figure 8 Constant pressure and constant volume expansion ratios as a function of Ø for Kellingley coal, walnut dusts and cornflour.*

2005; Tamanini and Ural, 1992) and so the present ISO 1 $m^3$ results are in very good agreement. This indicates that the test equipment and experimental procedures were reliable. The turbulent flame speeds in these six corn flour explosions was 12 m/s with a standard deviation of 8%. The flame speed for corn flour was significantly higher than the 8 m/s for walnut shell dust explosions in Fig. 5 and the $K_{st}$ for walnut dusts in this explosion was 105, which is exactly in proportion using the flame speed ratio from the corn flour flame speed measurements. This was a general feature of the results for several dusts that the turbulent flame speed and $K_{st}$ were linearly related as shown in Fig. 6. This shows that a more fundamental parameter, the flame speed, could be measured in the ISO 1 $m^3$ vessel rather than $K_{st}$. Andrews and Phylaktou (2010) have showed that $K_{st}$ or $K_G$ and the burning velocity are linearly related and this is demonstrated experimentally, for the first time to our knowledge, in Figure 6.

The turbulent flame speeds as a function of dust concentration as an equivalence ratio are shown in Figure 7 for a range of dusts including two biomass nut shell dusts. Other pulverised biomass were not studied as they would not pass through the C tube dust injector as they were too fibrous, but nut shell dusts are close to coal as they shatter when milled. The equivalence ratio is corrected for the dust that does not participate in the explosion using the procedure of Satter et al. (2012). All the dusts had a maximum reactivity in terms of the flame speed for very rich mixtures with Ø=1.5 for Kellingley coal and 2.5 for walnut dusts and corn flour. Pistachio nut shell dust and lycopodium powder were not explored over the full range of Ø as they were mainly used in a related programme on MEC. However, Figure 7 does show that both were more reactive for the same Ø than any of the other dusts tested.

The laminar flame speeds were derived from the turbulent flame speeds by dividing by the turbulent parameter β = 4.0. These laminar flame speeds are also shown in Fig. 7. To convert these to a laminar burning velocity the laminar flame speeds were divided by the adiabatic expansion ratio at constant pressure and three of the adiabatic flame temperature calculations as a function of Ø are shown in Figure 8. This shows that for the rich mixtures where the flame speed was highest, the flame temperature was low and this would make the expansion ratio low. The resultant laminar burning velocities for the various dust-air mixtures are shown in Fig. 7 and the peak values were 0.15 m/s for coal and 0.55 m/s for walnut dusts and corn flour. These measurements are in good agreement with those in the literature (Wolanski, 1995) but with a greater reliability and less data scatter. For coal dust at 33 μm particle size Smoot et al. found a burning velocity of 0.2 m/s and for corn flour Dahoe et al. (2002) found a peak value of 0.55 –

0.62, depending on the shape of the stabilized flame used. Both of these measurements are in good agreement with the present work.

### 4. Conclusions

The ISO 1 $m^3$ dust explosion vessel has been modified to enable flame speed measurements in the constant pressure period of flame propagation. The turbulence created by the air injection into the ISO vessel has been shown to accelerate laminar flames by a turbulence factor β of 4.0. This factor enabled the laminar flame speed to be derived and then the laminar burning velocity using the constant pressure flame adiabatic flame expansion ratio. This is considered to be a more reliable technique for the measurement of dust/air laminar burning velocities than other methods in the literature and used the standard equipment for dust explosion $K_{st}$ measurements.

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