# Flame Propagation of Pulverised Biomass Crop Residues and their Explosion Characteristics

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## 1 Abstract

Pulverised agricultural crop residues were investigated using the ISO 1 $m^3$ turbulent explosion vessel. This was modified to enable the spherical flame propagation flame speed and the heat release rate in $MW/m^2$ to be determined. From the turbulent flame speed, the laminar flame speed and laminar burning velocity and global heat release, $MW/m^2$, were determined. In addition the equipment was used to determine the biomass explosibility, $K_{st}$ (= $dP/dt_{max}V^{1/3}$), and the minimum explosion concentration (MEC). Two Pakistani crop residues bagasse (B) and wheat straw (WS) were investigated. Particle size distribution, elemental and proximate analysis and surface morphology for the raw powders and for their post explosion residues were carried out. It was found that these crop residues have explosibility characteristics comparable to wood biomass powders. MEC values as low as equivalence ratios of 0.18 to 0.3 were found which were lower than for gaseous hydrocarbons, but similar to other measurements for biomass using the Hartmann explosibility equipment. Peak turbulent flame speeds were measured at 3-4 m/s. There was a significant post explosion residue of unburned material which was shown to have an increase in char content relative to the raw biomass, while the volatile content was reduced. The BET surface area of the post explosion residue of bagasse was higher than that of the wheat straw residue, showing a higher release of volatiles for bagasse with a more porous char residue in the burnout indicating higher reactivity. These crop residues are a viable renewable fuel for existing coal power plants or as a basis for a new generation of small scale steam power generators in Pakistan.

## 2 Introduction

Worldwide interest is growing in biomass crop residues as an energy source, due to their short rotation cycle, ease of availability and low cost [1]. For Pakistan crop residues could be the sustainable basis for 40%+ of the existing electrical power consumption. However, there is little fundamental information on the combustion and explosion properties of pulverised agricultural biomass and this work aimed to provide such data. Crop residues contain higher ash than wood, which can be reduced by water washing by 60-80% [2]. Further reduction can be achieved with acid or base washing depending upon the type and amount of the minerals in the ash content. Biomass crop residues can be employed separately or in combination with coal to reduce fossil fuel $CO_2$ emissions [3, 4]. The application of pulverised crop residue dusts in power plants requires the assessment of the

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explosibility properties to maintain the safe working environment. Also the flame speed is a required design parameter in burner design [5].

# 3 Experimental Methodology

This work investigated the flame propagation characteristics of two biomass crop residues bagasse (B) and wheat straw (WS), which are abundantly available in Pakistan. The agricultural residues were coarse milled in Pakistan and then milled in Leeds to less than 63µm using an ultrafine grinder prior to their chemical characterization. An ISO $1m^3$ dust explosion vessel was used, but the standard dust injection system using a 'C' ring disperser [6] would not pass the fibrous particles that occur in woody and plant biomass after milling. The 'C' ring will only pass spherical type particles and nut dusts are a biomass that does operated with the standard dust injector [10]. For woody biomass and plant based biomass a new disperser was required and a spherical grid injector was developed and calibrated [11], similar to an explosion suppressant injector [6]. This would disperse woody and plant biomass milled to <63µm, but would not disperse larger particle sizes. A further problem with woody and plant pulverised biomass was the low bulk density, which resulted in the standard 5L external dust injection pot being too small to hold sufficient mass of biomass powder. To overcome this, a 10L external pot was developed and calibrated to give the same flame speed and $K_{st}$ as for the 5L pot with C ring disperser [12]. This modified ISO vessel dust injection system was used in the present work.

The ISO 1 $m^3$ dust explosion vessel was modified to enable the flame speed to be determined using linear arrays of mineral insulation exposed junction thermocouples. These measured the time of flame arrival as the time of the first measureable temperature rise, the dead time was minimal due to the size of the thermocouple exposed junction, 0.5mm, and for a flame speed of 1 m/s this is a 0.5ms uncertainty in flame arrival time which is the same for each thermocouple and hence not an error in the determination of flame speed. The thermal lag in the thermocouple response is irrelevant as the aim was not to measure the flame temperature, but the time of flame arrival. Three linear thermocouple arrays were used to determine the flame speed in three directions at $90^o$ to each other. If the three flame speeds were similar than a spherical flame had been achieved and this was then a valid measurement of the spherical flame speed. Satter et al. [13] have demonstrated for turbulent gas flame in the present equipment that repeat measurements of flame speed and burning velocity can be made with a 95% confidence of +/- 8%. For dust explosions they showed that the spherical flame speed repeatability was a 95% confidence of 16% of the mean value [13]. The greater data variability was due to the extra variability of the dust dispersion in addition to the randomness of turbulence.

Two Keller type-PAA/11 piezo-resistive pressure transducers were mounted in the explosion vessel to record the explosion pressure history and one pressure transducer is placed in the 10L dust pot. The response time of these pressure transducers was less than 1ms and their factory calibration accuracy was certified at <1%. The error in the determination of the deflagration index, $K_{st}$ ($= dP/dt_{max}V^{1/3}$), was also < 1%. However, the main cause of variation in the measurement of $K_{st}$ was the variability of turbulence and the randomness of the dust dispersion. In repeat dust explosion tests Satter et al. [13] showed from repeat tests using cornflour dust that $K_{st}$ 95% confidence interval was 12% of the mean value. This is better than the 16% confidence of the measurement of flame speed, as the rate of pressure rise is a mean measurement that essentially surface averages the flame propagation. The flame speed measurements were carried out a three radial lines and hence would show more variability than the rate of pressure rise repeatability.

A feature of the biomass dust explosions was that only about half of the dust was burnt and at the end of the experiment when the vessel was opened, there was a large quantity of explosion debris, which was mainly the original dust [10, 14]. This showed that the concentration injected was not the concentration that the flame propagated through. At the end of the test the debris was vacuumed out of the vessel and weighed. This enabled the mass of dust that burned in the test and from this the burned dust equivalence ratio could be determined. However, this burned equivalence ratio was further corrected for the ash that was adding in the residue sample due to the burning of the raw samples and this is how the results are expressed in terms of concentration. In addition the dust that did not burn

was analysed in the same way as the raw dust. The accuracy of this correction for the unburned mass of injected biomass is poor as it is difficult to ensure that all the unburned biomass was collected, the weighing of the unburned biomass in the filtered collection bags had <1% error. To account for uncollected unburned material 5% was added to the collected mass as a reasonable estimate of the amount left in crevices inside the vessel. Repeat tests indicate that the measurement of the unburned mass had a repeatability of 5% of the measured value.

Table 1. Chemical Characterisation of Bagasse and Wheat straw in comparison to other samples

| **Biomass** | **C daf. (%)** | **H daf. (%)** | **N daf. (%)** | **S daf. (%)** | **O daf. (%)** | **$H_2O$ (%)** | **VM (%)** | **FC (%)** | **Ash (%)** | **CV (MJ/ kg)** | **Stoich A/F (g/g)** | **Stoich. ($g/m^3$)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bagasse** | 55.6 | 7.3 | 1.3 | 0.1 | 35.7 | 7.2 | 67.1 | 5.6 | 20.1 | 15.6 | 7.5 | 221.3 |
| **Wheat Straw** | 50.6 | 6.4 | 1.4 | 0.07 | 41.5 | 6.8 | 60.7 | 9.7 | 22.8 | 14.5 | 6.4 | 268.4 |

# 4 Experimental Results

Chemical characterisation of the two crop residues are presented in Table 1 together with the stoichiometric A/F, computed from the elemental composition. The actual stoichiometric A/F including the ash and water content of the fuel is used in the computation of the equivalence ratio, Ø, in the reported results [10]. Both agricultural biomasses had a high ash content, which was based on the raw unwashed biomass.

An example of the flame arrival time vs. distance plots is shown for the three arrays of Type K thermocouples in Fig. 1. The flame propagation was reasonably symmetrical and this shows that the flame propagation was spherical. The average flame speed was determined for a range of biomass dust concentrations, as shown in Fig. 2. This shows that Bagasse had a higher peak flame speed than for wheat straw. Wheat straw also burned over a wider range of rich mixtures than bagasse. In the lean region the two agricultural waste dusts had a similar flame speed. The maximum turbulent flame speeds were determined as 3.8m/s and 3m/s for bagasse and wheat straw dusts respectively. The peak flame speed for wheat straw dust occurred at a burnt Ø of 1, but for bagasse dust it occurred at Ø = 2.5.

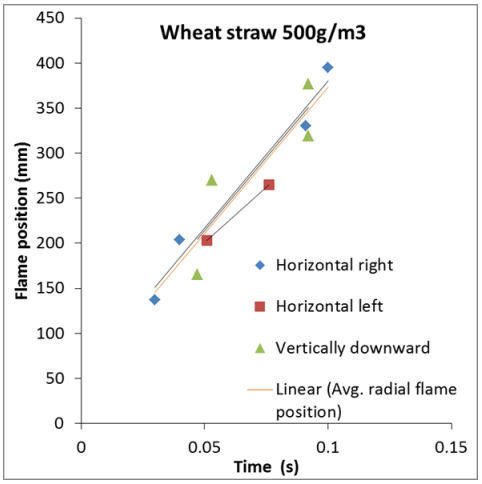



Figure 1. Example of the flame arrival time as a function of distance, the flame speed is the slope of the line.

The deflagration parameter, $K_{st} = dP/dt_{max}V^{1/3}$, is shown in Fig. 2 to be higher for bagasse dust in comparison to wheat straw dust, in agreement with the flame speed results. Also the peak to initial pressure ratio was higher for bagasse dust, indicating that it had a higher flame temperature. The flame speed and $K_{st}$ results showed that bagasse dust was more reactive than wheat straw. A good correlation was found between the turbulent flame speed and the $K_{st}$ reactivity parameters as shown in Fig. 3.

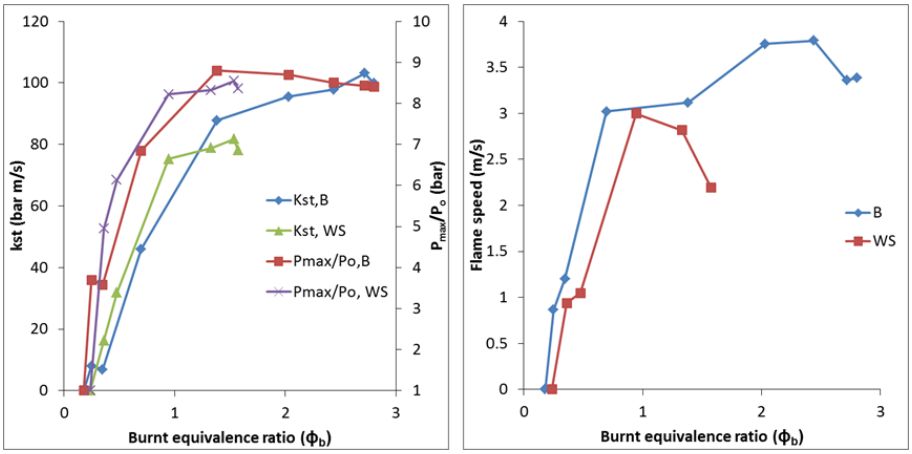



Figure 2. Comparison of $K_{st}$, $P_{max}/P_o$ and flame speeds of crop residue dusts Bagasse and Wheat straw against burnt equivalence ratio

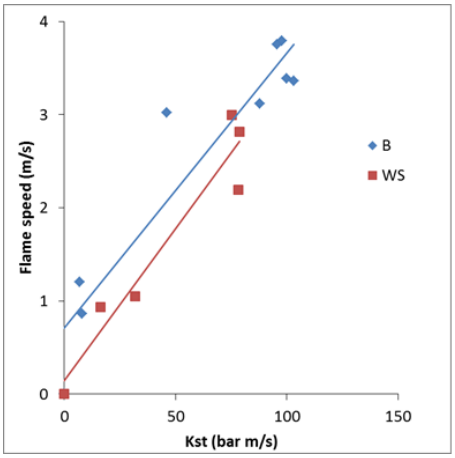



Figure 3. A correlation of flame speed vs. $K_{st}$ for crop residue dusts

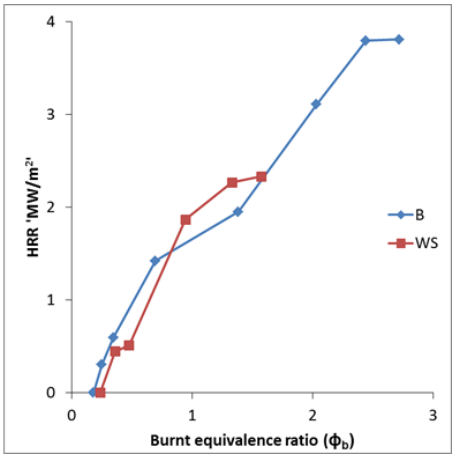



Figure 4. Heat release rate as a function of burnt equivalence ratio for crop residue dusts

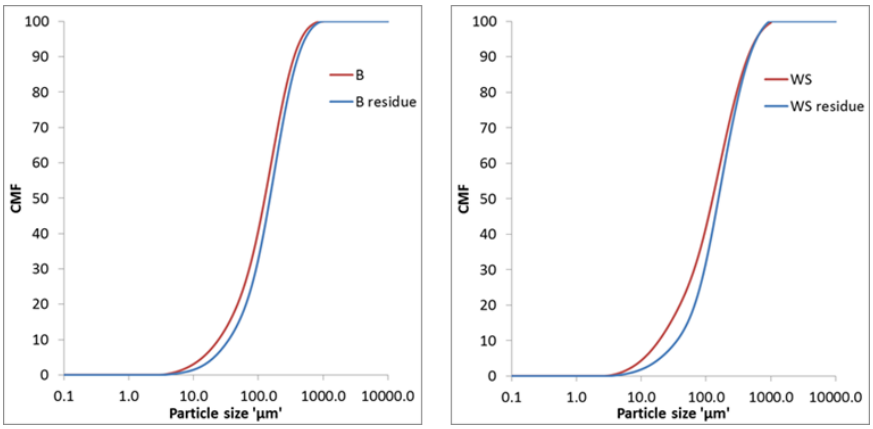
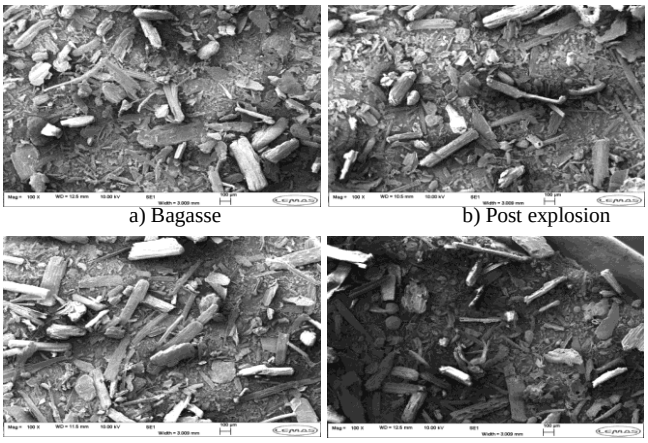



Figure 5. PSD of selected crops and their post explosion residues. Left: Bagasse dust. Right: Wheat straw dust

The maximum heat release rate of these crop residue dusts was determined using the following relationship [15].

$$HRR = \frac{(S_{ft.}\rho_{u.}GCV)}{E(1 + {}^{A}/_{F})}$$

where $S_{ft}$= Turbulent flame speed (m/s), $\rho_u$= density of air (Kg/m$^3$), GCV= Gross calorific value (MJ/Kg), E= Expansion factor ($P_{max}/P_o$) and A/F=Air to fuel ratio by mass.
The results are shown in Fig. 4 which shows that the HRR increases with Ø and continues to increase in the rich region. This is mainly driven by the flame speed measurements in Fig. 2 which continue to go faster for rich mixtures. There is no decrease in the flame speed or HRR in the rich region as would occur for rich gaseous mixtures. The peak heat release rate for the biomass fuels was 3.8 MW/m$^2$ for bagasse and 2.3 MW/m$^2$ for wheat straw. These are well in the range of existing pulverised coal furnaces where 2-5 MW/m$^2$ is typical [16]. Thus it may be concluded that the turbulence conditions and turbulence flame propagation rates in the ISO 1 m$^3$ vessel are comparable with those for conventional pulverised coal plants.



a) Bagasse b) Post explosion

c) Wheat straw d) Post explosion

Figure 6. Surface morphology comparison of crop samples and their post explosion residues

The MEC were determined after correcting for actual burnt concentration. It was found that bagasse dust had a lean limit burnt Ø of 0.18 whereas wheat straw dust had Ø = 0.24. This is a further indication that bagasse was more reactive than wheat straw. These lean limits are in good agreement with other woody biomass dusts and are much lower than for the coal and hydrocarbon dusts [9, 11].
The particle size distribution (PSD) of the raw biomass samples were lower than their post explosion residues as shown in Fig. 5. This might be due to swelling of the particle due to evolution of volatiles in the combustion. BET surface area and surface morphology analysis showed a more porous structure for bagasse than wheat straw for the raw material and for the post explosion residues. The ash content of wheat straw resulted in the formation of cenospheres from silica in the ash. The residues were mainly the original material, but with some charring of part of the material. Previous work by the authors has shown that the residue occurs because the explosion induced expansion wind ahead of the flame carried dust with it into the wall where it was compressed against the wall. The flame impinges on this layer and chars the outer surface. However, most of the layer remains unburned and is original dust that did not participate in the explosion.

# 5 Conclusions

Bagasse and wheat straw from Pakistani crop residues were investigated for their implementation as substitute fuel for coal in the power generation plants. Lean flammability limits for these crop residues were in the range of 0.18-0.3 equivalence ratio compared to 0.5 or higher for the conventional fuels. Peak turbulent flame speeds were 3-4m/s. These crop residues after controlling their ash content can be used for the generation of electricity in small local power generation plants close to the farms.

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