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Saeed, MA, Slatter, D, Andrews, GE orcid.org/0000-0002-8398-1363 et al. (2 more authors) (2016) *Combustion of Pulverized Biomass Crop Residues and Their Explosion Characteristics*. *Combustion Science and Technology*, 188 (11-12). pp. 2200-2216. ISSN 0010-2202

<https://doi.org/10.1080/00102202.2016.1212604>

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<https://doi.org/10.1080/00102202.2016.1212604>

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COMBUSTION SCIENCE AND TECHNOLOGY VOL. 188 , ISSUE 11-12, Pages 2200-2216, 2016

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Abstract

Two Pakistani crop residues bagasse (B) and wheat straw (WS), both with high ash content, were milled to $<63\mu\text{m}$ and the ISO 1 m³ explosion equipment was used to investigate flame propagation in the dispersed cloud of pulverised biomass. Their turbulent flame speed was measured and the K_{st} ($dP/dt_{max}V^{1/3}$) and comparison was made with two pulverised coal samples. Minimum Explosion Concentration (MEC) values for B and WS were, in terms of the burnt dust mass equivalence ratio (ϕ) 0.2 ϕ to 0.3 ϕ , which was leaner than for the coal samples. These MEC were lower than had previously been determined using the Hartmann explosion tube, and this was considered to be due to the 10 kJ ignition energy in the 1 m³ equipment and 4J spark energy in the Hartmann explosion tube, which extended the lean limit in the 1 m³ equipment. Peak turbulent flame speeds were 3.8 m/s for B and 3.0 m/s for WS compared with 3.5–5.2 m/s for the two coal samples. The peak K_{st} was 103 bar m/s for

bagasse and 80 bar m/s for wheat straw and the two coal samples had peak K_{st} of 78 and 120 bar m/s. Overall the agricultural biomass and coal samples had a similar range of reactivity. Thus these agricultural crop residues are a viable renewable fuel for co-firing with coal or as 100% biofuel operation of steam power plants.

Keywords: Combustion, Flame propagation, Explosibility

1 Introduction

Short rotation crop residues are a potential low cost and abundant clean substitute for coal for decentralised power generation plants. For Pakistan crop residues, forestry, seed oil plants and nut shells are substantial biomass resources. These waste biomass resources in Pakistan could be the basis for 78% of the current peak electricity supply and hence could be a sustainable electricity supply alternative to the current use of fossil fuels (Saeed et al., 2015c). Worldwide interest is growing in biomass crop residues as an energy source, due to their short rotation cycle, ease of availability and low cost (McKendry, 2002). However, there is little fundamental information on the combustion and explosion properties of pulverised agricultural biomass and this work aimed to provide such data.

This pulverised form of biofuels has a low lean flammability limit or minimum explosion concentration (MEC) in equivalence ratio terms and this indicates a high reactivity of pulverised agricultural biomass (Saeed et al., 2015a). This high reactivity leads to fire and explosion hazards and this work measured the K_{st} and MEC which are required for explosion protection design. There have been many biomass dust fires or explosion incidents in recent years. The latest UK incident in 2015 was a wood floor mill explosion in Macclesfield where four deaths occurred together with complete destruction of the plant.

Crop residues contain higher ash than wood due to the use of fertilisers in their cultivation and the absorption of silica from wind-blown dusts. However, these ash levels are similar to those in coal and although they act as an inert mass that reduces the flame temperature they are not sufficiently high to prevent an explosion risk. Biomass crop residues can be employed separately or in combination with coal to reduce fossil fuel CO₂ emissions (Nuamah et al., 2012, Nussbaumer, 2003). The present work also measures the biomass turbulent flame speed, laminar burning velocity and turbulent HHR/m².

2 Materials tested

Biomass	C daf %	H daf %	N daf %	S daf %	O daf %	H ₂ O %	VM %	FC %	Ash %	CV MJ/kg	Stoich A/F g/g	Stoich actual g/m ³
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The flame propagation and explosion characteristics of two biomass crop residues bagasse (B) and wheat straw (WS) were investigated. These are agricultural waste materials which are abundantly available in Pakistan. The agricultural residues were coarse milled in Pakistan and then milled to less than 63µm using an ultrafine grinder prior to their chemical characterization. The biomass dust explosions were compared with two reference coal samples results which have been previously published (Huéscar Medina et al., 2015).

Table 1 Properties of the biomass and reference coal samples

Bagasse (B)	55.6	7.3	1.3	0.1	35.7	7.2	67.1	5.6	20.1	15.6	7.5	220
Wheat Straw (WS)	50.6	6.4	1.4	0.07	41.5	6.8	60.7	9.7	22.8	14.5	6.4	266
Colombian Coal (C Coal)	81.7	5.3	2.6	0.86	9.6	3.2	33.7	47.8	15.3	26.4	11.2	135
Kellingley Coal (K Coal)	82.1	5.2	2.97	2.8	6.96	1.7	29.2	50.0	19.1	25.0	11.6	131

The elemental analyses of the dusts are shown in Table 1. From the elemental analysis the stoichiometric air/fuel ratio (A/F) has been calculated by carbon, hydrogen and oxygen balance on a dry ash free basis (daf). The actual A/F is calculated from the stoichiometric A/F by mass using Eq. 1.

$$\text{Actual A/F} = \text{Stoichiometric A/F} [1 - (x_w + x_a)] \quad (1)$$

Where x_w and x_a are the mass fractions of the moisture and ash contents in the sample respectively. In dust explosion research the dust concentration has been commonly expressed in terms of g/m^3 and Andrews and Phylaktou (2010) were the first to relate dust explosion data to the dust equivalence ratio, ϕ (Andrews and Phylaktou, 2010). The actual A/F for stoichiometric combustion has been converted in Table 1 to units of g/m^3 using Eq. 2

$$\text{Stoichiometric concentration, } \text{g/m}^3 = 1200/\text{A/F}_{\text{stoich}}. \quad (2)$$

The constant of 1200 is the density of air at ambient conditions, 1200 g/m^3 .

	SiO ₂	CaO	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	Na ₂ O	MgO	P ₂ O ₅	Others
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As received	Bagasse	48	9.4	9.1	3.5	5.2	4.53	3.1	1.7	14.47
	Wheat straw	59	5.4	10.5	0.6	9.5	1.8	2.2	0.7	10.3

Table 2 Comparison of ash contents in raw residues

Table 1 also shows the water, volatile, fixed carbon and ash fractions of the biomass and coal samples determined using TGA analysis. The material was heated to 110°C in nitrogen and the weight loss was the water content. Heating continued to 910°C in nitrogen and the weight loss was the volatile content. Air was then introduced and carbon burnt so that the weight loss was the fixed carbon. The remaining weight was the ash fraction. The composition of the ash fraction is shown in Table 2. This was dominated by SiO₂ with a wide range of other constituents at mainly <10% for individual components.

3 Experimental Methodology

An ISO 1m³ dust explosion vessel was used as shown in Fig. 1. However, the standard dust injection system using a ‘C’ ring disperser (Eckhoff, 2003) would not pass the fibrous particles that occur in woody and plant biomass after milling. The ‘C’ ring will only pass spherical type particles. Nut dusts are biomasses that do operate with the standard C ring dust injector (Sattar et al., 2012b), as nut particles are fractured in milling in a similar way to coal. For woody biomass and plant based biomass a new disperser was required and a spherical grid injector was developed and calibrated, similar to an explosion suppressant injector, which is shown in Fig. 2. 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, the existing 5L pot used with the ISO 1 m³ dust explosion vessel was extended to 10L volume with a 5L pot extension as shown in Fig. 1. The 10L external pot was calibrated to give the same flame speed and K_{st} as the 5L dust injection pot with the C ring disperser using cornflour as a reference dust (Sattar et al., 2012a). The air pressure in the external vessel was reduced from 20 bar for the 5L vessel to 10 bar for the 10L vessel, so that the total mass of external air to disperse the dust remained the same (Sattar et al., 2012a). The ignition delay for the spherical disperser with the 10L dust injection pot was calibrated against the standard C ring disperser using cornflour to have an ignition delay between start of injection and ignition of 0.5s, compared with the standard C ring delay of 0.6s. This modified ISO vessel dust injection system was used in the present work.

The ISO 1 m³ dust explosion vessel was modified to enable the flame speed to be determined using linear arrays of mineral insulation exposed junction Type K 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° 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.

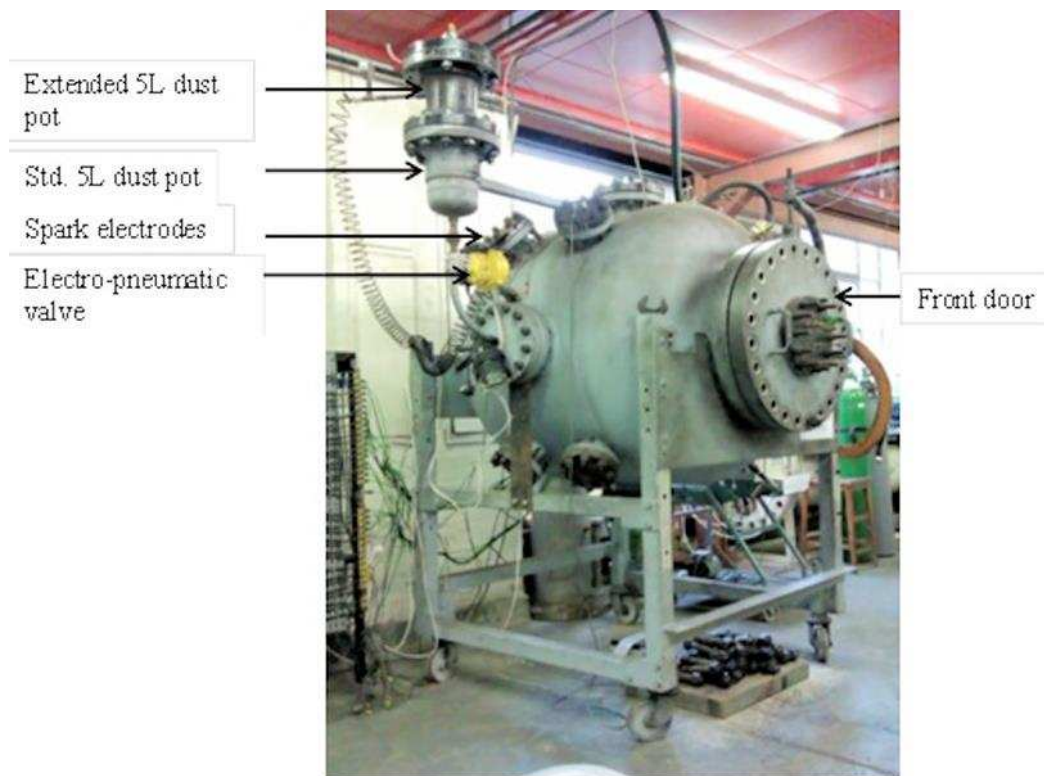


Figure 1. Modified ISO 1m³ explosion vessel

Sattar et al. (2014) have demonstrated for turbulent gas flames in the present equipmental 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 (Sattar et al., 2014). The greater data variability was due to the extra variability of the dust dispersion in addition to the randomness of turbulence. The thermocouple arrays were all in the first half of flame travel



Figure 2. The spherical grid dust disperser.

where the pressure rise is low. In a spherical vessel when the flame is half way across the vessel the volume burnt is 1/8 but the mass burnt is about 1/50 or 2% and the pressure rise is proportional to the mass burnt. Thus the flame speed in this work and the burning velocities derived from this were at constant pressure (Sattar et al., 2014).

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 was 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%. The main cause of variation in the measurement of K_{st} was the variability of turbulence and the randomness of the dust dispersion. Sattar et al. (Sattar et al., 2014) showed from repeat tests using cornflour dust that the 95% confidence interval for the measured K_{st} was 12% of the mean value. This was 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 on three radial lines and hence would show more variability than the rate of pressure rise repeatability.

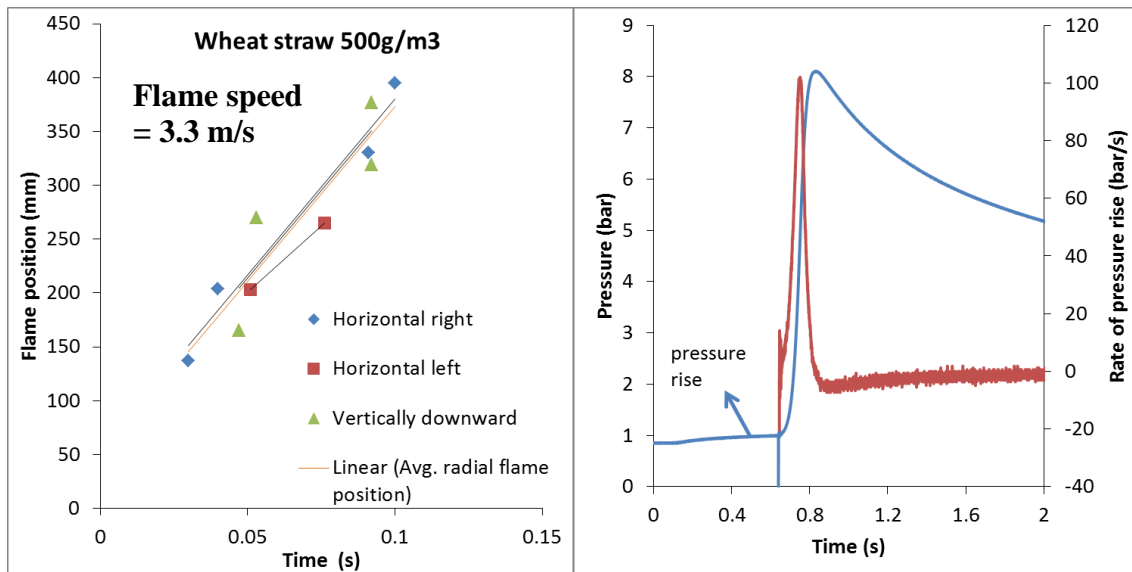


Figure 3. Example of the pressure rise with rate of pressure rise and flame arrival time as a

Fig. 3 shows, for the present fibrous type agricultural waste biomass, an example of the pressure trace and rate of pressure rise measurements. Also shown is an example of the flame arrival time vs. distance plots for the three arrays of type K thermocouples. Fig. 3 shows that the flame propagation was reasonably symmetrical, which means that the flame propagation was reasonably spherical. The turbulent flame speed is the slope of the mean line and was 3.3 m/s for the data in Fig. 3.

A feature of the biomass dust explosions was that only about half of the dust was burnt. At the end of the experiment when the vessel was opened there was a large quantity of unburned powder on the floor of the vessel. This indicates that all the dust placed in the external pot does not all take part in the explosion and so there is uncertainty over the concentration of the dust that the flame propagated through. At the end of each dust explosion the debris was collected using a standard vacuum dust extractor into a bag filter. The bag filter was weighed before and after the extraction to determine the mass of dust that was not burned. Analysis of this large quantity of explosion debris showed that it was mainly the original dust (Sattar et

al., 2014, Sattar et al., 2012a, Sattar et al., 2012b). This showed that the concentration injected was not the concentration that the flame propagated through. The measured weight of unburned dust enabled the mass of dust that burned in the test to be determined and from this the burnt dust equivalence ratio could be determined.

The weight of dust remaining after the explosion included the ash from the biomass dust that did burn. As the ash fraction of the dust was known, as in Table 1, the weight remaining could be corrected for this, using Eqs. 4 and 5. This then allows the equivalence ratio of the dust that did burn to be determined.

$$\text{Corrected vessel residue} = \frac{\text{Vessel Residue collected}}{1 + \text{Ash fraction}} \quad (3)$$

$$\text{Actual burnt mass} = \text{Injected mass} - \text{corrected vessel residue} \quad (4)$$

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. The dust that did not burn was analysed in the same way as the raw dust and this showed that it was predominantly unburned original dust.

The source of this unburnt dust was the explosion induced wind entraining the relatively large dust particles ahead of the flame and eventually carrying them onto the wall where they were compressed by the pressure rise. After the pressure fell due to heat losses at the end of the explosion, this wall dust fell onto the floor of the vessel, where it was collected after the explosion (Sattar et al., 2012b). There was some evidence of partial pyrolysis of the outer

layer of this dust, but this was a small effect and only made a small change in the composition of the residue dust from the original dust (Slatter. et al., 2013).

4 Particle Size Distribution and SEM Analysis

Although all the particles in the present work were sieved below 63 μm the laser scatter method of particle sizing showed that there was still a significantly wide size distribution, as shown in the volume size distribution in Fig. 4. Both figures compare the raw biomass size distribution with that of the residue left after the explosions. The bagasse particle size was

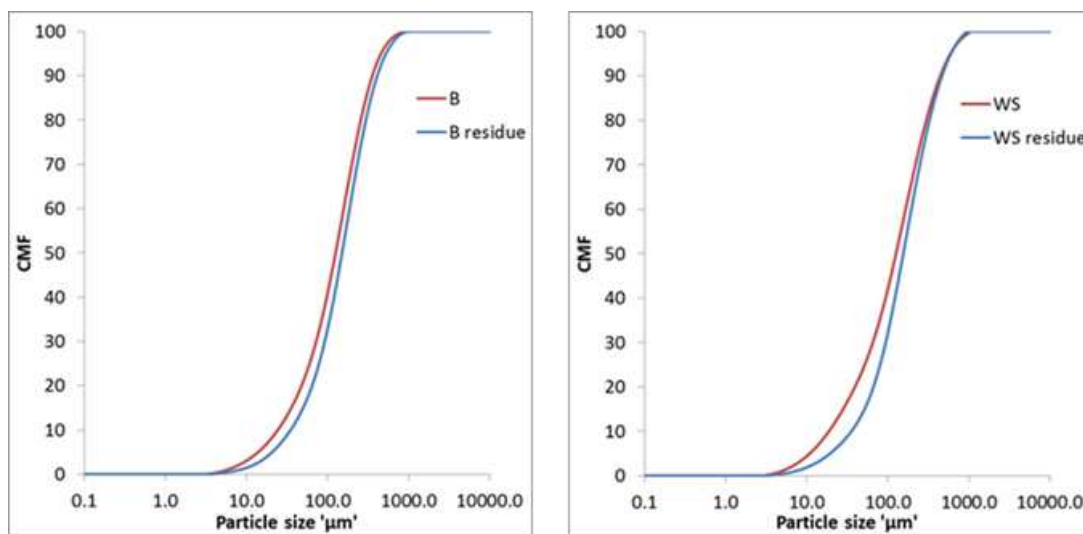


Figure 4. PSD of selected crops and their post explosion residues Left: Bagasse dust (B) & Right: Wheat straw dust (WS)

Table 3 Mean Size of the Biomass and Residues

Sample	D (0.1)	D (0.5)	D (0.9)
	μm	μm	μm
Bagasse	24.3	126	356
Wheat straw	18.8	12	442
Bagasse residue	35.0	151	409
Wheat straw residue	35.6	155	464
Columbian coal	6.8	28	85
Kellingley coal	5.0	26	65

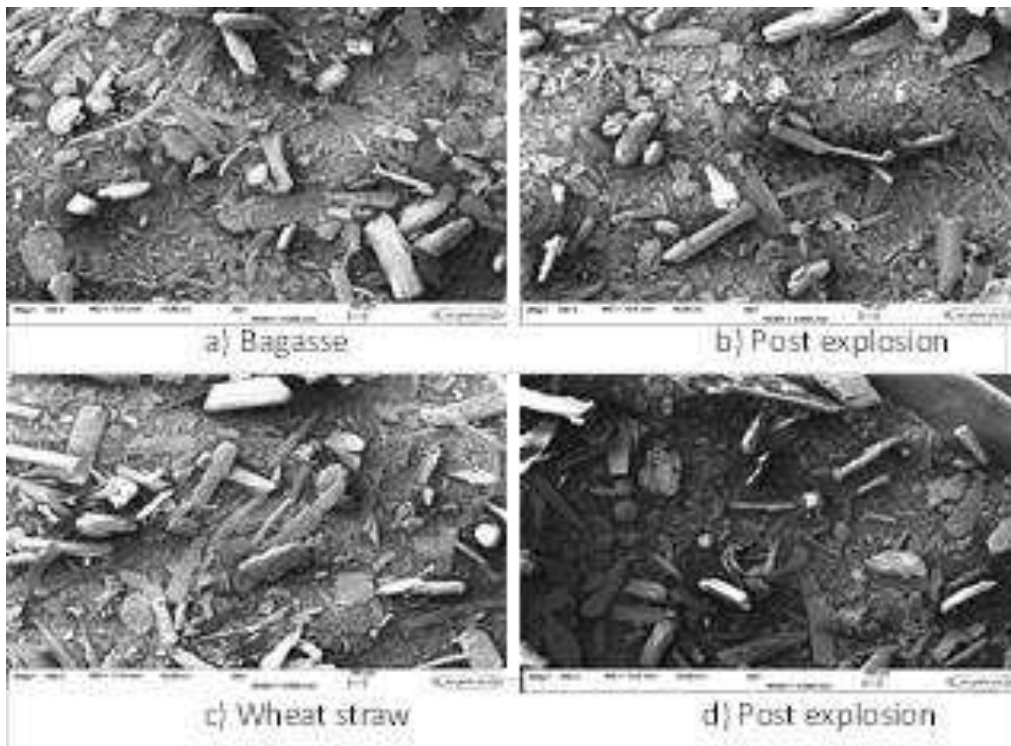


Figure 5. Surface morphology comparison of crop samples and their post explosion residues

slightly lower than wheat straw, which would be a further reason for the reactivity to be higher. For both bagasse and wheat straw the size distributions were similar for the raw material and the residues. There were reduced fines in the biomass residues, but this difference was insufficient to conclude that the flame had propagated only in the fines. The mean size distributions for 10%, 50% and 90% of the size distribution are shown in Table 3. The size distribution for the two coal samples are also shown in Table 3 and these shows that this was a much finer fraction than all the biomass samples.

The size distributions in Fig. 4 and Table 3 show that in spite of sieving to $<63\mu\text{m}$ the biomass particles were relatively coarse and only the coal particles were most of the particles substantially below the $63\mu\text{m}$ sieve size. This implies that the biomass particles were long cylinders with a diameter $<63\mu\text{m}$ but a length greater than this, whereas the coal particles

were more cubic. SEM analysis of the biomass particles, as shown in Fig. 5 for the raw biomass and the residues, show that there were many large particles that were long cylinders. The laser light scattering particle size method interprets these as spheres of equivalent light scatter. The SEM analysis in Fig. 5 shows little difference between the raw biomass and the biomass residue after the explosion. This also shows that the residue was predominantly the original material with a similar size distribution.

5 Turbulent Flame Speed

The average flame speed for bagasse and wheat straw in comparison to the two coal samples is shown as a function of the burned dust equivalence ratio in Fig. 6. The range of mixtures investigated for wheat straw was less than that for bagasse because less wheat straw material was sent from the source in Pakistan. The maximum turbulent flame speeds were determined as 3.8m/s and 3.0m/s for bagasse and wheat straw dusts respectively, showing that bagasse was more reactive than wheat straw. The reason for this was the higher volatiles, higher hydrogen and lower oxygen content of bagasse compared with wheat straw.

If the two biomasses are compared at the same burnt equivalence ratio, such as at $\phi = 1$ in Fig. 6, then the flame speeds are the same at 3.0 m/s. Bagasse has an increase in reactivity relative to wheat straw only for rich burned gas ϕ . Fig. 6 shows that bagasse has the same peak flame speed as Kellingley coal but lower than the flame speed of Colombian coal. The main reason was the higher ash contents in the biomass samples that acted as inert solid mass in suppressing the flame propagation. Colombian coal had the lowest ash content and the highest CV of all four fuels and this was part of the reason it was the most reactive. Both of the coal samples has significantly narrow size distributions that for biomass, as shown in Table 3. This will also tend to lead to a higher flame propagation rate. Colombian coal was

significantly finer than Kellingley coal and this will be part of the reason the flame speeds were higher for Columbian coal. The similar flame speeds of the two biomass samples with Kellingley coal, in spite of the much lower CVs, indicates that the fuel CV is not the determining factor in the flame speed.

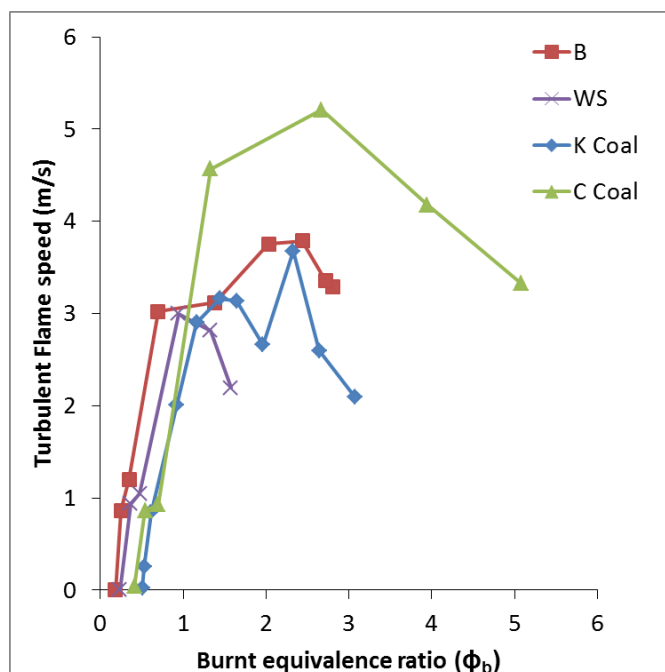


Figure 6. Flame speeds of Bagasse and Wheat straw in comparison to coals as a function of the burnt Φ

The peak flame speed for wheat straw dust was at an equivalence ratio of stoichiometric ($\Phi=1$), but for bagasse dust and both coal samples it was at $\Phi = \sim 2.5$. This is difficult to explain as for wheat straw there was a clear reduction in the flame speed for burned dust equivalence ratios >1 , as expected for gas explosion flame speeds (Sattar et al., 2014). However, the wheat straw results are more unusual as most dusts continue to have high reactivity for rich mixtures as for bagasse and the two coal samples in this work (Andrews and Phylaktou, 2010, Eckhoff, 2003). The occurrence of a high reactivity for rich dust/air mixtures was not commented on until this was pointed out by Andrews and Phylaktou (2010), as explosion results had never previously been expressed in equivalence ratio terms.

A possible explanation of this phenomenon is the action of the explosion induced wind ahead of the flame on dust particles that have a wide size distribution. This is the case in the present work and it was shown above that the size range for both agricultural dusts ranged up to 400 μm for $D_{90\%}$ with some particles larger than this. The flame speeds of about 3m/s will have an unburnt gas velocity ahead of the flame of about 2.7 m/s, due to the expansion of the burnt gases. This gas velocity will entrain the particles ahead of the flame. The finest particles will travel with the gas velocity ahead of the flame and eventually some will be compressed on the wall. These finer particles will propagate the initial flame front. However, the larger particles will lag the gas velocity due to drag effects and eventually these will be overtaken by the flame front. These large particles will then be flash heated by the burnt gases and as the mixture is rich these large particles will be gasified releasing CO and hydrogen and the expansion of these gases on release will increase the pressure. High CO in the burnt gases for rich walnut shell dust explosion was measured by Sattar et al. (2012b). There is insufficient oxygen for these gasification gases to be burnt. The richer the mixture the more large particles are gasified behind the flame front and hence the flame speed keeps increasing due to volume release and expansion of gasification gases from the large particles. It is shown below that a consequence of this is that the peak pressure remains high for all the rich mixtures tested. However, the reason for the flame speeds to be reduced for wheat straw cannot be explained if this is the mechanism for bagasse. It will be shown below that the other reactivity parameter, K_{st} , does not support the reduction in reactivity for rich mixtures shown by the flame speed measurements for wheat straw.

The laminar burning velocity of the pulverised dust/air mixtures may be determined (Sattar et al., 2014) from the turbulent flame speed. The laminar flame speed is first determined by using the calibrated turbulence factor ($\beta = \text{turbulent/laminar flame speed ratio}$) for the

spherical flame injector, which was calibrated at $\beta = 4.0$ (Sattar et al., 2012a). The laminar flame speed can then be used to determine the laminar burning velocity by dividing the flame speed by the constant pressure expansion ratio, E . In the present work this was taken as the measured P_m/P_i as advocated by Cashdollar (1996). These results are shown in Fig. 7 and show very low laminar burning velocities that would be very difficult to measure without the turbulence in these experiments, as the flame would be strongly influenced by buoyancy, as for gas explosions with these low laminar burning velocities (Andrews and Bradley, 1973).

The low reactivity of the biomass and coal dusts relative to gases is easily seen by comparing the values of the turbulent flame speeds in Fig. 6 with the laminar flame speeds of methane air, which has a peak value of about 3.0 m/s in large vessels, as used in the present work (Andrews and Bradley, 1972a). The present turbulent flame speeds are only just higher than the laminar flame speeds for hydrocarbon-air gas explosions. With a turbulence factor of 4 this gives laminar flame speeds roughly $\frac{1}{4}$ those of hydrocarbon-air mixtures.

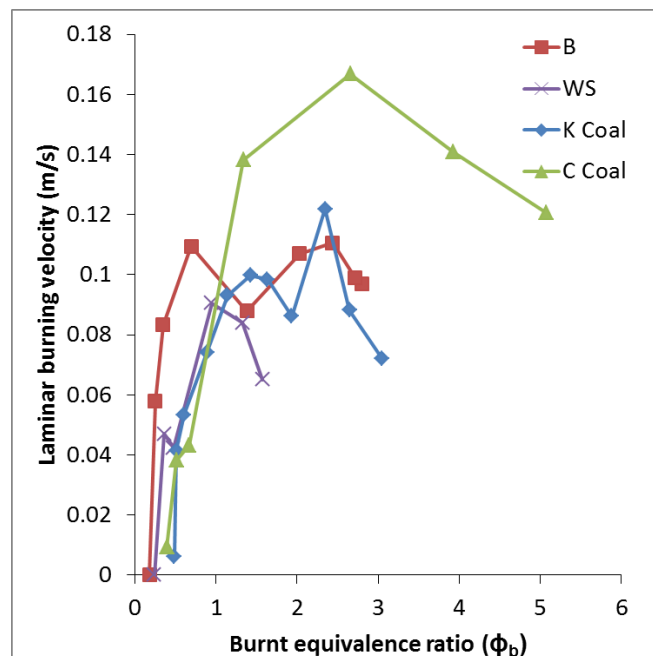


Figure 7. Variation of the laminar burning velocity with Φ_{burnt}

In pulverised coal burners the air is preheated to about 600K using an exhaust heat exchanger and the laminar burning velocity increases as the square of temperature (Andrews and Bradley, 1972b). This gives a factor of 4 increase in the burning velocity at 600K compared with 300K. Thus the turbulent flame speeds in Fig. 6 will be close to the laminar flame speeds at 600K.

6 Heat Release Rate per Flame Area, MW/m².

The maximum heat release rate of these crop residue dusts was determined using Eq. 5 (Huéscar Medina et al., 2015).

$$HRR = \frac{(S_{ft} \cdot \rho_u \cdot GCV)}{E(1+A/F)} \quad \text{MW/m}^2 \quad (5)$$

where S_{ft} = Turbulent flame speed (m/s), ρ_u = density of air (kg/m³), GCV = Gross calorific value (MJ/kg), E = Expansion Ratio and A/F = Air to fuel ratio by mass.

The expansion factor E, is the unburnt gas to burnt gas density ratio at the constant pressure of the flame speed measurements. However, dust flame temperature and density are not easy to calculate with ash and water present and the constant volume expansion ratio is often used for E, which is measured by P_{max}/P_o (Cashdollar, 1996), values of which are reported below.

The HRR results are shown in Fig. 8 which shows that the HRR increases with burnt gas equivalence ratio and continues to increase in the rich region. This is mainly driven by the flame speed measurements in Fig. 6 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. For 20% excess air, the heat release rate for the biomass fuels was 1.5 MW/m² for bagasse and 1.7 MW/m² for wheat straw, compared with 2.5 – 4 MW/m² for the two coal samples. For the stoichiometric ϕ_{burnt} , the biomass HRR was about half of that of coal for the same turbulence level. This difference in HRR/m² arises from differences in the turbulent

flame speed, expansion ratio, stoichiometric A/F and CV in Eq. 5. The lower CV and stoichiometric A/F for biomass compared to coal roughly cancels out in Eq. 5 and the main differences in HRR were due to flame speed and expansion ratio differences.

The peak heat release rate for the biomass fuels was 3.8 MW/m² for bagasse and 2.3 MW/m² for wheat straw, compared with 6.5 – 7 MW/m² for the two coal samples. However, the peak

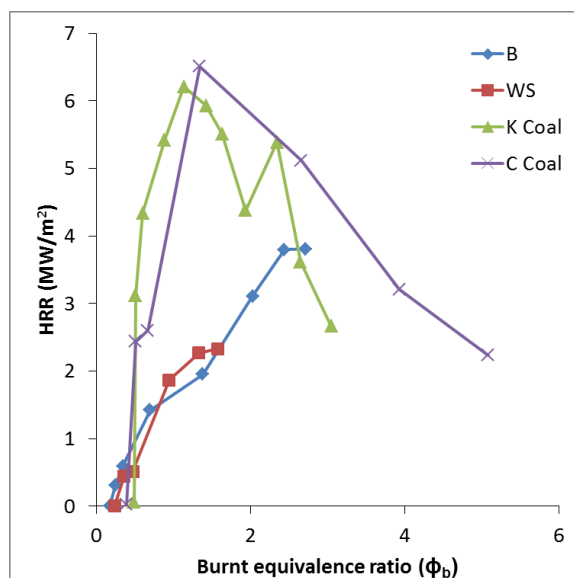


Figure 8. Heat release rate as a function of burnt equivalence ratio for crop residue dusts heat release for both coal samples occurred at a leaner mixture than for the biomass samples. This is likely to be due to the lower volatile fraction and the lower release of gasification products for rich mixtures with coal. Coal has to gasify carbon or char which requires a high residence time, whereas biomass is predominantly gasified volatiles from the particles, as Table 1 shows a much lower fixed carbon in biomass particles.

The values of HRR in Fig. 5 are in the range of existing coal furnaces with 20% excess air, where 1-5 MW/m² is typical (Jenkins et al., 1998; Basu, 2006) which are lower HRR than the current peak HRR measurements for the two coal samples, but similar to their values for 20% excess air. Thus, it may be concluded that the turbulence conditions and turbulence flame propagation rates in the ISO 1 m³ vessel are comparable with those for conventional coal

plants for the same equivalence ratio. Although the two biomass results have a lower HRR than coal their values are within the range that current coal combustion plants operate. Hence, biomass should be capable of being used as an alternative fuel without major changes to the coal combustion equipment. The lower HRR for biomass will result in pulverised flames with a longer flame and this has been observed on pulverised coal power plants retrofitted for biomass combustion (personal communication Drax power station).

7 Minimum Explosion Concentration (MEC).

The lean flammability limit, LEL, or minimum explosion concentration, MEC, for dusts in the ISO 1 m³ spherical explosion vessel has been conventionally determined on the basis of the injected concentration. When about 50% of the mixture does not burn it is clear that the injected concentration is not the appropriate concentration to base the MEC. Also the ISO procedures for MEC determination only require the following concentrations to be tested:1000, 750, 500, 250, 125, 60, 30 and 15 g/m³. The MEC is defined as the dust concentration that does not explode. Thus, if say 60 g/m³ explodes and 30 g/m³ does not then the MEC is 30 g/m³ and there is no requirement in the standards to test intermediate concentrations. This is why tables of MEC for dusts have lots of materials with MEC of 60 or 30 g/m³ (Eckhoff, 2003). This is a poor accuracy procedure and it is not sensible to have such a crude method for the determination of MEC for dusts.

In the tube method for the determination of gas/air flammability limits, the LEL should be determined with a resolution of 10% of the LEL for gaseous concentrations >2% or 0.2% for concentrations below this (European-Standard, 2003, Saeed et al., 2015b). The value for the last ignition should be reported and the concentration gap that was tested with no ignition should be within 10% of the last positive ignition. The standard essentially sets the LEL at up

to 10% below the concentration that had a measured flame propagation. In equivalence ratio, ϕ , terms where for hydrocarbon –air mixtures the lean limit is about $\phi = 0.5$, the resolution of this limit is $\phi < 0.05$. Most reported LEL for gases resolve the lean limit better than this and normally report to 0.01ϕ . In dust concentration terms the 0.05ϕ resolution for a pure hydrocarbon dust such as polyethylene is 4 g/m^3 and for a cellulose or biomass type dust with a stoichiometric A/F ratio of 6/1 by mass (200 g/m^3) it would be a resolution of the MEC to 10 g/m^3 , with normally better resolution than this (European-Standard, 2003). This is a much better resolution of the MEC than is required in the legislated dust explosion MEC procedures. In the present work the MEC was determined as the leanest mixture that just did not explode.

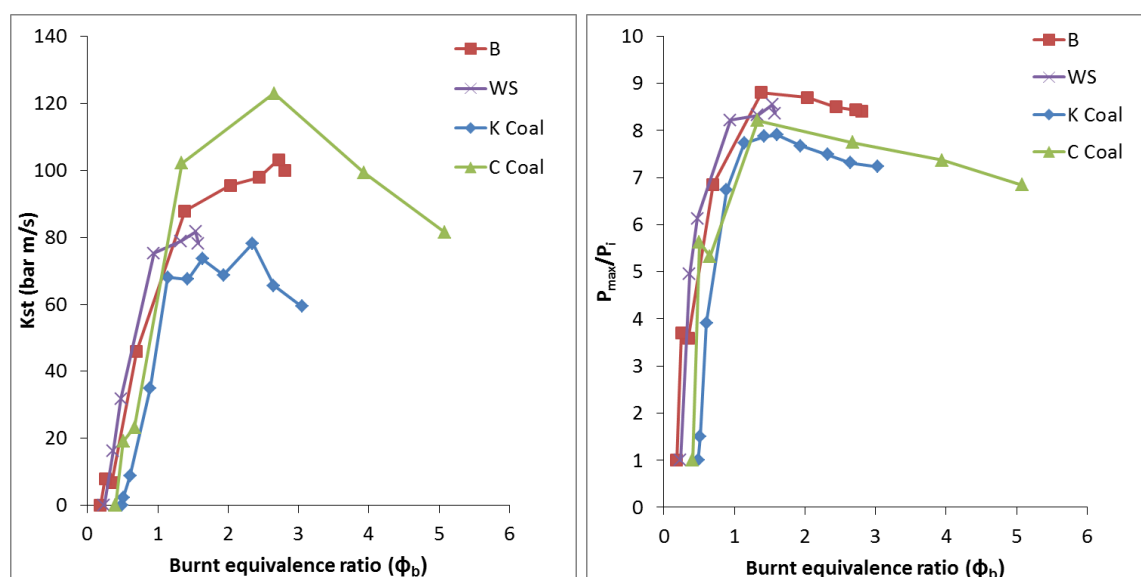
The determination of the mixture concentration at the lean flammability limit is difficult in the ISO 1 m^3 vessel as in addition to the unburnt injected dust there is additional unburnt material due to the convective rise of the flame kernel near the lean limit (Andrews and Bradley, 1973), which leads to a combustion inefficiency loss of particulate material. The procedure of deducting the mass of residue from the injected mass would result in an extremely lean concentration at the MEC. Sattar et al. (2012a,b) introduced a procedure where the fraction of the dust that burned at the maximum reactivity was assumed to be the fraction that burned at all mixtures if there was no buoyancy. This procedure was used in the present work and on this basis it was found that bagasse dust had a lean limit at the burnt equivalence ratio of 0.22ϕ and wheat straw dust had and MEC of 0.29ϕ , as shown in Figs. 6 and 8. The leaner MEC for bagasse 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 (Slatter, 2013).

The authors have previously determined the MEC for bagasse and wheat straw using the Hartmann equipment (Saeed et al., 2014). This gave the lean limit as 0.52Ø for bagasse and 0.9Ø for wheat straw. For materials with a low ash and water content, such as corn cobs and peanut shells, the MEC was close to 0.2Ø, as found in the present work for bagasse and wheat straw. The high MEC for bagasse and wheat straw for the Hartmann equipment was correlated with other results as a function of water and ash inert mass in the dusts (Saeed et al., 2014). The present MEC results for bagasse and wheat straw are incompatible with those previously measured on the Hartmann equipment. A possible explanation of this difference is the action of the 10kJ chemical ignitor energy in the 1 m³ equipment and the 4J electrical continuous spark ignition energy in the Hartmann. For low reactivity dusts, such as the present agricultural residues with high ash content, Bartknecht (1993) has shown that the lean flammability limits for gases and low reactivity dusts are sensitive to the ignition energy, with high ignition energy giving a leaner MEC (Bartknecht, 1993). However, more work is required on a more reliable method of determining the MEC as both the current methods have experimental errors (Saeed et al., 2015b).

8 Deflagration Parameter, K_{st} .

The deflagration parameter, $K_{st} = dP/dt_{max} V^{1/3}$, is shown in Fig. 9 (a) as a function of the burnt equivalence ratio. Fig. 9 (a) shows that K_{st} was higher for bagasse dust in comparison to wheat straw dust, in agreement with the flame speed results. The bagasse K_{st} results were still increasing at ϕ_{burnt} of 2.7, whereas the flame speed in Fig.7 had levelled out at $\phi_{burnt} = 2.5$. Thus it is not clear whether the maximum reactivity ϕ_{burnt} had reached its maximum value. For wheat straw dust Fig. 9 shows that K_{st} was very similar to that of bagasse up to a ϕ_{burnt} of 1, but that for richer mixtures K_{st} was lower for wheat straw than bagasse and reached a peak K_{st} of 80 at ϕ_{burnt} of 1.5. At this ϕ_{burnt} bagasse had a K_{st} of 90 and was still increasing to its

maximum of 105 at a ϕ_{burnt} of 2.7. However, we did not have enough pulverised wheat straw dust to operate with richer mixtures and confirm that a K_{st} of 80 was the maximum value. Similarly the comparison with coals has the same trend as that of flame speed. Wheat straw dust had a similar K_{st} to Kellingley coal. The peak K_{st} for bagasse and Colombian coal were at same burnt equivalence ratio, but Columbian coal had a significantly higher peak K_{st} at 125 compared to 105 bar m/s for bagasse.



a) K_{st} vs. burnt equivalence ratio

b) P_{max}/P_i vs. burnt equivalence ratio

Figure 9. Reactivity of the selected residues in comparison to Kellingley coal (K Coal) and Colombian coal (C Coal)

The ratio of the maximum pressure to the initial pressure is shown in Fig. 9 (b) as a function of the burnt equivalence ratio. This is the measured expansion ratio for constant volume combustion, that has been used in the laminar burning velocity determinations discussed above. The ratio was slightly higher at 8.8 for bagasse dust than wheat straw dust, where the peak was 8.5. However, for both dusts the peak pressure occurred at the same ϕ_{burnt} of 1.5. The higher peak pressure rise indicates that bagasse had a higher flame temperature than wheat straw and this would be expected as Table 1 shows that the measured calorific value

and volatile content was higher for bagasse and the ash content lower. Both these agricultural residues and coals have a good comparison for P_m/P_i ; however there was more mass burning and higher P_m/P_i for agricultural residues in comparison to coals.

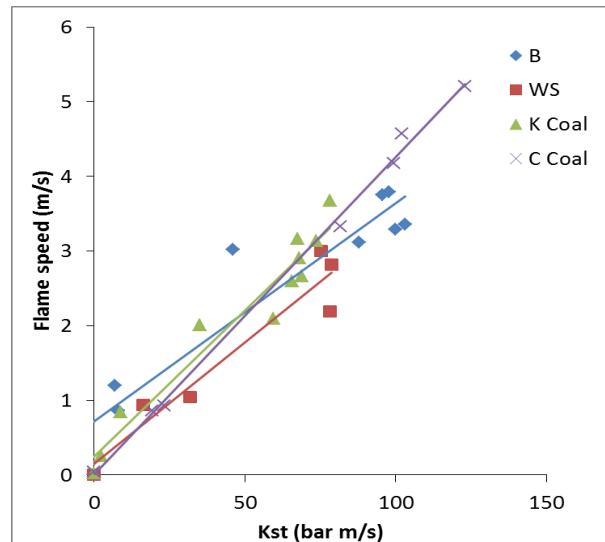


Figure 10 Correlation of K_{st} and turbulent flame speed

The turbulent flame speed and K_{st} are both parameters that measure the mixture reactivity and should be linearly correlated (Andrews and Phylaktou, 2010). K_{st} is shown as a function of the measured turbulent flame speed in Fig. 10. The level of agreement is relatively poor, but there is a correlation. For wheat straw for example there are three data points with K_{st} 75 – 80 bar m/s, but with a wider variation of the turbulence flame speed of 2.2 - 3 m/s.

A curious feature of the bagasse results was that for mixtures richer than ϕ_{burnt} of 1.5, P_m/P_i decreased as ϕ_{burnt} increased whereas K_{st} continued to increase. The peak flame temperature was at $\phi_{burnt} = 1.5$ as that was where the peak pressure occurred. The model given above can explain these results. This is that large particles lag behind the flame front and are pyrolysed in the burnt gases and this heating reduces the burnt gas temperature and the pressure falls. The rich mixture has no oxygen and thus gasifies the large particles releasing CO and H₂. The sudden volume expansion of these pyrolysed large particles results in an increase in the peak

rate of pressure rise and hence in K_{st} . The increased mass into the burnt gases without heat release cools the burnt gases and the peak pressure falls.

Table 4 Comparison of the present results with those for other biomass.

Samples	$\phi_{peak\ kst}$	Peak Pm/Po	Peak K_{st} (bar m/s)	Peak turbulent flame speed (m/s)	References
Bagasse	2.72	8.8	103.1	3.79	This work
Wheat Straw	1.57	8.5	81.7	3.0	This work
Pistachio nut shells	2.4	9.3	82	3.7	Sattar (2012b)
Walnut shells	2.8	9.4	98	5.1	Sattar (2012b)
Pne 1	4.2	9.0	109	3.7	Huescar (2013)
Pine 1 (torrefied)	2.15	9.1	138	5.6	Huescar (2013)
Spruce	1.9	8.8	81	3.4	Huescar (2014a)
Raw Spruce (torrefied)	2.6	8.9	95	3.6	Huescar (2014a)
US Pine 2	2.5	9.0	105	4.5	Huescar (2014b)
US pine 2 (torrefied)	2.0	8.8	115	4.4	Huescar (2014b)
Colombian Coal	2.65	8.2	122.9	5.2	Huescar (2015)
Kellingley Coal	2.34	7.9	78.2	3.67	Huescar (2015)

The present results for the maximum turbulent flame speed and K_{st} are compared in Table 4 with those for other biomass. This shows a consistent pattern with all the biomass studied giving K_{st} in the range 80 – 138 and this is very similar to the range of the two coal samples. The turbulence flame speeds range from 3 – 5.6 m/s with the highest value for torrefied pine

and the lowest value for the present wheat straw results. The two coal samples also fall within this range of flame speeds.

9 Conclusions

Bagasse and wheat straw from Pakistani crop residues were investigated for their implementation as substitute fuel for coal in electricity generation. Lean flammability limits for these crop residues were lower at 0.18-0.30 compared with gaseous hydrocarbons. Peak turbulent flame speeds were 3-4m/s and K_{st} were 82 and 103 bar m/s. These reactivity parameters were similar to those for woody biomass and similar to two coal samples. These crop residues can be used for the generation of electricity in pulverised flame power plants.

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