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FLAME SPEED AND K$_{ST}$ REACTIVITY DATA FOR PULVERISED CORN COBS AND PEANUT SHELLS

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Abstract

Power generation using waste material from the processing of agricultural crops can be a viable biomass energy source. However, there is scant data on their burning properties and this work presents flame speed and explosion K$_{st}$ data for two agricultural waste materials: corn cobs and peanut shells. Both parameters were measured on the ISO 1 m^3 dust explosion equipment. Two coarse size fractions of corn cobs (CC) and peanut shells (PS) of size less than 500 µm were tested using the Leeds 1 m^3 vessel and were compared with two pulverized coal samples. This is typical of the size fraction used in pulverized coal power stations and of pulverized biomass currently used in power generation. The explosion parameters minimum explosive concentration (MEC), rate of pressure rise (dP/dt), deflagration constant (K$_{st}$), peak to initial pressure rise (P$_m$/P$_i$), turbulent and laminar flame speeds were determined using a calibrated hemispherical disperser in the 1 m^3 vessel. MEC were measured in the range of 0.6-0.85 in terms of burnt equivalence ratio, Ø$_{burnt}$, which were comparable to the coal samples. The measured K$_{st}$ (25-60 bar m/s) and turbulent flame speeds (~1.3 m/s) were lower than for coal, which was a reflection of the lower calorific value. These results showed that these crop residues are technically feasible power plant fuels to burn alongside coal or as a renewable biofuel on their own.

Keywords: Explosibility, Flame propagation, Biomass Energy

1. Introduction

Agricultural waste crop residues are a renewable and economical fuel for low carbon power generation (Saeed et al., 2014). Agricultural countries like Pakistan have the potential to exploit these local agricultural waste materials as renewable fuels for power generation and this will help its rural development. Saeed et al. (2015d) proposed that power plants of about 10MW$_e$ could be based on the agricultural wastes in a 10km radius around the plant. It was estimated that utilization of crop wastes have the potential to fulfil 76% of the electricity demand of Pakistan (Saeed et al., 2015d). These agricultural waste biomass fuels have higher moisture and ash content as compared to woody biomass and this will influence their combustion properties (Saeed et al., 2014). Thermal treatments in combination with pelletization will improve the fuel quality (Saeed et al., 2015a) and ease of handling (Kaliyan, 2008). The residues studied in this work were corn cobs and peanut shells. These are major crops in Pakistan and were sourced from Pakistan and milled in Pakistan. Fig. 1 shows that both of these crops have a consistent or increasing growth from 2009 and are thus available each year for continual energy generation.
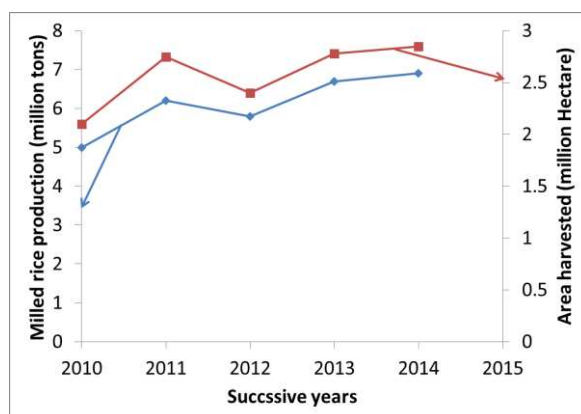
Fig. 1: Production of selected crops in Pakistan for the successive years (Indexmundi, 2015)

Feeding of these compact fuel pellets in the silos results the generation of fines that carry fire and explosion risks. In electric power generation these fuels are used in pulverized form and therefore milled prior to their combustion. This pulverized state of fuel is very reactive due to more exposed area which gives a rapid volatile release and fast burning. The propagation of flames in mixed pulverised biomass and air is crucial to the design of combustion systems for burning these fuels. These biomass fuels in pulverised form have an explosibility risk, which also involves a flame propagating through a pulverised biomass and air mixture and thus is the same process as occurs in stabilised flames (Andrews and Phylaktou, 2010, Eckhoff, 2003).

Table 1: Recent biomass dust fire/explosion incidents

Date	Type	Plant	Summary
July 17, 2015	Fire + expl.	Bosley Mill Macclessfield, UK	➢ Powerful explosion and fire resulting in the collapsing of the building. ➢ 4 deaths and 20 injured. ➢ Cause is still under investigation.
February 05, 2015	Fire	Boyne City wood pellet factory	➢ Fire broke out in a dust collector. ➢ Suppression activated but failed to put out the fire. ➢ No injuries were reported.
April 28, 2014	Fire + expl.	German Pellets plant in Woodville	➢ Dust caught fire inside silo and resulted in explosion affecting another silo next to it. ➢ No injuries were reported.
March 29, 2014	Fire	Energex American plant	➢ An office and sawdust storage warehouse damaged. ➢ One firefighter was injured.
Sept. 03, 2013	Fire + expl.	Rotokawa wood pellet plant,	➢ Fire and explosion originated inside the silo and duct system. ➢ No injuries were reported.
April 09, 2013	Fire	Charleston Pellet plant	➢ Fire caught by the pellets started in the pellet plant ➢ No injuries were reported.
April 05, 2013	Fire	Dewys Manufacturing in MARNE, Mich.(WOOD)	➢ Five fire departments were called to Dewys Manufacturing in Marne after a fire. ➢ The fire started in a dust collecting unit in the building. No one was hurt and the fire did not

spread to any other part of the structure.

There have been many incidents of fire/explosion in the biomass plants and similar grain storage facilities, on average one incident was reported every day (Abbasi and Abbasi, 2007). Some of recent incidents of biomass fire/explosions are summarized in Table 1 (Industrial-Fire-World, 2015).

Utilization of the biomass as feed-stock for power generation plants partially with coal or independently involves many problems that need to be addressed (Tumuluru et al., 2011). Consistency in the availability of the selected biomass reserves is of prime importance and this is better for biomass pellets and best for torrefied biomass. Also the balance of the harvest of biomass with consideration of their growth time has to be maintained for environmental sustainability. Most woody biomass takes up to a hundred years for their growth and a large proportion of wood is used as construction material in industry. A major sustainability criteria is that the annual harvest of wood is the inverse of the full growth time, which is generally 1-2% for wood. This is similar to the amount of brash in forest which currently has no value. However, crop residues are different in that and in countries like Pakistan more than one crop a year can be produced. All of the non-food part of the crops is then available each year as waste biomass (Saeed et al., 2015d). However, they have limited production with some share of these crop wastes used for cattle feed.

A disadvantage of agricultural waste biomass is the high ash content, which acts as an inert mass and lowers the flame temperature and creates slag and corrosion problems in boilers. Saeed et al. (2014) showed that milling agricultural waste biomass concentrated the ash in the finer fraction which are more reactive. The ash in agricultural waste crop residues can be minimized by water and/or acid washing. Milling of agricultural waste fibrous biomass is also a problem area and burning of larger particles sizes would enable lower cost utilization of these materials. However, due to the high volatile content of biomass they do not need to be as fine milled as coal (Tumuluru et al., 2011) to be equally reactive and this will be shown in this work.

Biomass is primarily composed of cellulose, hemicellulose and lignin that decompose upon exposure to heat. Pyrolysis components involve free and bound moisture, tar, incondensable gases, char and ash contents. The bound moisture is collected in the tar that can be separated from bio-oil (Bridgwater et al., 1999). These are composed of complex compounds such as furfural, levoglucosan, phenol, 1,4:3,6-dianhydro-α/β-d-glucopyranose, acetic acid etc. Further fractionation results in the formation of simple gases like CO, CO_2, CH_4, H_2 and other C_xH_x (Wang et al., 2014). The characterization of these volatiles is dependent on the particle size distribution, heating rate and the heating temperature. Higher heating rate with higher temperature increases the production of hydrogen due to more decomposition of lignin that releases more hydrogen (Neves et al., 2011). These pyrolysis gases play an important role in the flame propagation due to substantial amount of volatiles that dominate the combustion with relatively low char yields and char combustion. Also the low activation energies for their volatiles release rate make them more reactive than coal samples (Saeed et al., 2015b). Biomass can be either co-fired with coal or burnt on its own (Sami et al., 2001).

The velocity of the dust/air mixture from the mill to the burner must be higher than the burning velocity otherwise there can be a flashback into the supply tube and mill. However, the velocity cannot be too high or the flame stability will be poor and these aspects of burner

design need to know the burning velocity of the pulverized biomass/air mixture. These parameters are also critical in the explosion protection design procedures.

2. Experimental Methods

Ultimate analysis was performed on a Flash 2000 Thermal Scientific Analyser in which a small amount of sample was burned in pure oxygen at 1800°C and converted to the respective combustion gases CO_2, H_2O, NO_2 and SO_2. These combustion gases were passed through a chromatographic column using a helium carrier gas, where they were separated and quantified using a thermal conductivity detector (TCD). Oxygen found by the missing mass and was not directly analysed. The elemental analysis as shown in Table 2 and was used for the determination of molar ratios of hydrogen and oxygen relative to carbon, H/C and O/C, on a dry ash free basis (daf) that were used for the calculation of the stoichiometric air to fuel ratio.

A Shimadzu 50 Thermo-gravimetric analyser (TGA) was used to determine the water, volatile, fixed carbon and ash content. The weight loss in nitrogen was determined as a function of temperature. The weight loss to 110°C and 910°C was the water and volatile content respectively. Air was then substituted for nitrogen and the weight loss was the fixed carbon content. The remaining weight as a proportion of the initial weight was the ash content. Bomb calorimetry was used to measure the gross calorific values of the samples. A Malvern Mastersizer 2000 was used to measure the size distribution and cumulative size of the samples. SEM analysis was performed using a Carl Ziess EVO MA15 scanning electron microscope.

A modified ISO $1m^3$ vessel, shown in Fig. 2a, was used for the determination of the pulverised biomass reactivity in terms of the deflagration parameter K_{st} ($=dP/dt_{max}V^{1/3}$) and the turbulent flame speed, S_T. The standard $1m^3$ dust explosion equipment operates by inserting the dust to be tested in an external 5L pot that is separated from the main vessel by a fast acting valve. This pot with the dust was pressurised to 20 bar prior to the test. The pot is connected to a 'C' ring with an array of holes that is designed to disperse the dust and air. The main vessel is partially evacuated so that when the compressed air is added the pressure is a standard atmosphere. The flow of air through the holes in the C ring creates turbulence as well as dispersing the dust. Turbulence decays rapidly with time after the end of injection and the results of this test depend on the turbulence present at ignition. This is controlled by the time delay between the external compressed air arriving in the vessel (determined from the rise in pressure of the vessel) and ignition of the mixture. In the standard C ring method this delay is 0.6s. The authors have used turbulent and laminar gas explosions in this vessel to show that the turbulence created with 0.6s delay gave a factor of 4 enhancement of the flame speed (Sattar et al., 2014).

A 2 D array of thermocouples were placed for measurement of flame speeds that will also show whether the flame is propagating uniformly and spherically, as assumed in the definition of K_{st}. This turbulent flame speed can be converted into a laminar flame speed by dividing by the above turbulence factor of 4.7 and then converted into the laminar burning velocity using expansion ratio, as determined by the measured peak to initial pressure ratio (Sattar et al., 2014). Unfortunately, the standard "C" ring injector does not work for pulverised coarse woody biomass, as the particles are compressed in the delivery tube and do not emerge from the injection holes. This occurs even where the woody biomass is sieved to <63 µm, as size

and SEM analysis of these particles shows that cylinders of diameter <63µm occur with lengths much greater and these block in the "C" ring. Several modifications were investigated, but for particles with sieved sizes >63 µm, as used in power stations and as occur in pellet store dusts, no method using the external pot to place the dust could be operated with coarse biomass dusts.
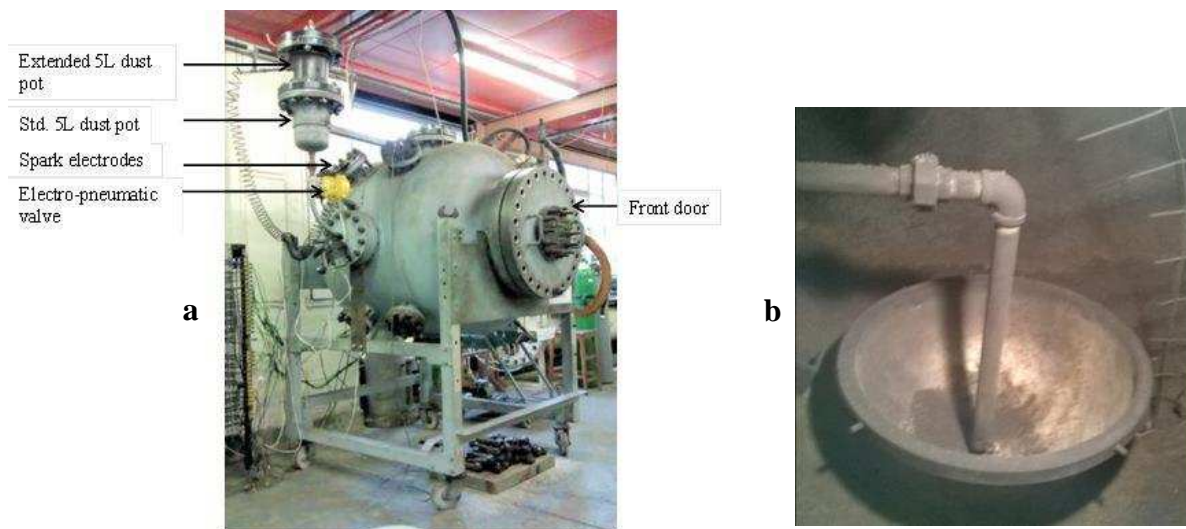
Fig. 2: a) Modified 1 m^3 vessel b) Hemispherical disperser

The principle of an externally based dust driven in by compressed air had to be abandoned and instead, the Hartmann method was used whereby the dust was placed inside the vessel in a chamber and dispersed with a blast of air. A hemispherical container was secured on the floor of the vessel, as shown in Fig. 2b, that was 0.4m diameter with a volume of 17L and could contain 3.5 kg of biomass particles with bulk density of 200 kg/m^3. This was used with compressed air from a 10L external volume at 20 bar pressure. The air was fed via a pipe the same size as the "C" ring to the bottom of the hemisphere and injected through a series of holes around and along the tube end, so that the same total hole area as for the "C" ring injector was used. Calibration of the injection system showed that an ignition delay of 0.5s was required to give the same explosibility indices for cornflour and Colombian coal as the standard ISO 1 m^3 design. This method of dispersion of the dust also gave a spherical flame. Calibration of the turbulence in this arrangement, as outlined above for the standard C ring, gave a turbulence factor of 4.7.

It was observed in both the standard ISO 1 m^3 equipment and the modified equipment shown in Fig. 2a, that about half of the nominal starting mass remained unburnt after the flame propagation in the hemisphere or on the bottom of the vessel (Sattar et al., 2012a, Sattar et al., 2012b). The composition of this unburnt mass was shown that of the unburnt original biomass with minimal change in composition. The unburnt mass was extracted using a vacuum cleaner into a filter bag and weighed. The equivalence ratio of the tests was corrected for the mass unburnt and is referred to as the burnt mass equivalence ratio, Ø$_{burnt}$. This included a correction for the proportion of the unburnt mass that was ash from the burnt biomass. Ø$_{burnt}$ is the actual concentration involved in the propagation of flame calculated using the Eqs 1 and 2.

$$Actual\ burnt\ mass = \frac{Injected\ mass - Vessel\ residue}{1 - Ash\ fraction} \qquad (1)$$

$$Burnt\ equivalence\ ratio, \emptyset_{burnt} = \frac{(\frac{Air}{Fuel})_{Stoichiometric}}{(\frac{Air}{Fuel})_{Acutal}} \quad (by\ mass) \qquad (2)$$

3. Corn Cob and Peanut Shell Characterisation

Two crop residues 'Corn cob' (CC) and 'Peanut shell' (PS) were investigated as they are typical of waste agricultural products in Pakistan. These agricultural residue samples were milled at source in Pakistan and it was this milled sample that was used in the explosions after sieving to <500µm. The TGA and elemental analysis of the two samples and of two coal samples for comparison are shown in Table 2. The two coal samples used for comparison were milled and sieved to <63µm and this is the main reason that they were more reactive as is shown in the results.

Table 2 shows that corn cobs and peanut shells have a high N and ash content which are undesirable, but both levels are about half those for coal. The differences in the stoichiometric A/F ratio have to be taken into account in the burner control for these fuels, a much higher mass flow of biomass is required compared to coal to deliver the same energy to the furnace. Table 1 also shows that these crop residues have higher volatile content and lower fixed carbon content compared to coal. In addition to higher volatiles, the rate of release of volatiles were faster than in the coal samples and occurred at lower temperatures, as shown by the TGA results in Fig. 3. Two peaks for the release of volatiles for the corn cob sample was caused by the decomposition of outer soft hemicellulose at the lower temperature and the decomposition of cellulose and lignin at the higher temperature. The calorific value was lower for corn cobs than peanut shells. Higher volatiles and their higher rate of release make corn cobs more reactive than peanut shells.

Table 3 shows the elemental and TGA analysis of the post explosion residues for the most reactive concentration, in comparison to their respective raw samples. For the corn cob residues the composition was very close to the original raw material for all parameters measured. In contrast the residues from the peanut shell dust explosions were significantly different. The biggest difference was the increase in ash, which is expected as the ash from the material that burns should accumulate with the residue alongside the material injected that did not burn. If only about 50% of the original material burns then the ash in the deposits should be about double that in the raw material and this occurs for the PS residues. The lack of an increase in ash for the CC is difficult to explain. The PS residues had a significant decrease in volatiles and increase in fixed carbon together with a decrease in O content.

Table 2: Chemical Characterisation of selected crop residues in comparison to coals (Huéscar Medina et al., 2015)

Biomass	Corn cobs (CC)	Peanut shell (PS)	Kellingley Coal (K Coal)	Colombian Coal (C Coal)
% C (daf.)	45.9	53.7	82.1	81.7
% H (daf.)	6.0	6.6	5.2	5.3
% N (daf.)	1.2	1.5	3.0	2.6
% S (daf.)	0.1	0.0	2.8	0.9
% O (daf.)	46.8	38.2	7.0	9.6
% H2O	7.1	7.0	1.7	3.2

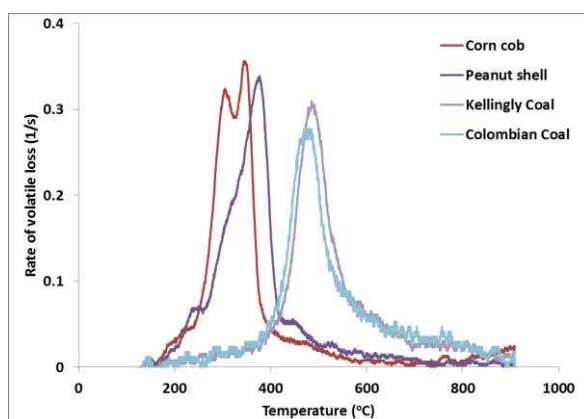|				
% VM	69.4	66.4	29.2	33.7
% FC	14.8	18.6	50.0	47.8
% Ash	8.8	8.0	19.1	15.3
CV MJ/kg$_{actual}$	16.7	19.7	25.0	26.4
CV MJ/kg$_{daf}$	19.6	23.2	31.6	32.4
Stoich. A/F g/g daf	5.4	6.9	11.6	13.1
Actual stoich. conc. g/m^3	264	205	131	135

Fig. 2: Rate of volatile loss for selected crop residues in comparison to coals

Table 3: Chemical characterization of the post explosion residues in comparison to their raw samples

Biomass	**Corn cobs (CC)**	**Post explosion residue CC**	**Peanut shell (PS)**	**Post explosion residue PS**
% C (daf.)	45.9	47.4	53.7	57.6
% H (daf.)	6.0	6.0	6.6	6.2
% N (daf.)	1.2	1.1	1.5	1.8
% S (daf.)	0.1	0.0	0.0	0.0
% O (daf.)	46.8	45.6	38.2	34.4
% H2O	7.1	6.2	7.0	5.8
% VM	69.4	67.6	66.4	58.2
% FC	14.8	17.5	18.6	20.2
% Ash	8.8	8.7	8.0	15.1
CV (MJ/kg)	16.7	17.2	19.7	19.2
Stoich. A/F (g/g)	5.4	5.5	6.8	7.3
Actual stoich. conc. (g/m^3)	264.2	256.4	204.6	207.8

This indicates some low temperature pyrolysis has occurred, with similar results to torrefaction. Why these two biomass behaved differently is not known. However, the post explosion residue is concluded to be predominantly the same as that of raw biomass.

4. Particle size distribution of the milled biomass

Table 4 shows the particle size distribution of the raw biomass (sieved to <500µm) and the post explosion residues. The two size distributions were very similar, again indicating that the residue was predominantly the original raw biomass. There was an increase in the proportion of fines and a decrease in the proportion of coarse material in the residues for both biomasses. However, for CC the surface average size decreased in the residue whereas for the PS the surface averaged size increased in the residue, but the changes were relatively small.

Table 4: Chemical characterization of the post explosion residues in comparison to their raw samples

Materials	D (10%)	D (50%)	D (90%)	Surface weighted mean	% <100µm
Corn cob	45.0	372.6	777.8	98.1	19
Post explosion corn cob	48.4	239.6	668.3	92.1	22
Peanut shell	24.3	176.1	698.5	63.5	39
Post explosion peanut shell	32.4	180.9	648.6	75.3	35

Table 4 shows that the raw biomass size distributions as milled were relatively coarse with over 50% of the mass >373µm for CC and >176µm for PS. The distribution of sizes in the samples and residues are shown in the SEM images in Fig. 4. There is no evidence in the size distribution or in the SEM images of the raw biomass and their residues, that only the fines burn in the explosion, as also proved by the minor difference of the % fraction<100µm in Table 4. The conclusion is that the fines and coarse material burn approximately with equal effectiveness and this was not expected.

SEM images in Fig.4 of molten layers of the burnt mass showed the formation of some ceno-spheres so there was some pyrolysis of the biomass. In the corn cob sample, more molten layers were observed in the post explosion residues than the peanut shell sample. The soft structure of corn cob facilitating the efficient release of volatiles is also supported by the volatile release plot in Fig. 3. Also smoldering of the biomass was experienced during milling of the corn cob sample, but not the peanut shell sample.

A physical model of the turbulent biomass flame front that fits the above evidence is that the explosion induced wind blows the dust ahead of the flame and eventually this dust is compressed into a layer on the walls. The flame then impinges on the wall and partially pyrolysis the outer layer, but the inner layer next to the wall remains the original biomass with the original size distribution. After the explosion this residue falls off onto the floor of the vessel (Sattar et al., 2012a, Sattar et al., 2012b, Slatter. et al., 2014). At the turbulent flame front the action of the explosion induced wind is for the fines to follow the gas flow and the coarse particles to lag behind and be enveloped in the products of reaction of the fines. The coarse material is then gasified in the hot combustion products of near stoichiometric burning of fines. This model explains why rich mixtures can burn with the generation of a high pressure, as will be shown in the results. In these biomass samples there are sufficient fines for lean mixtures to burn and to give a relatively lean MEC. However, the temperature is still sufficient to ignite the coarse particles and for lean overall mixtures they can then burn as there is surplus oxygen. For rich overall equivalence ratios the coarse particles are gasified by heating in the products of the combustion of the fines.
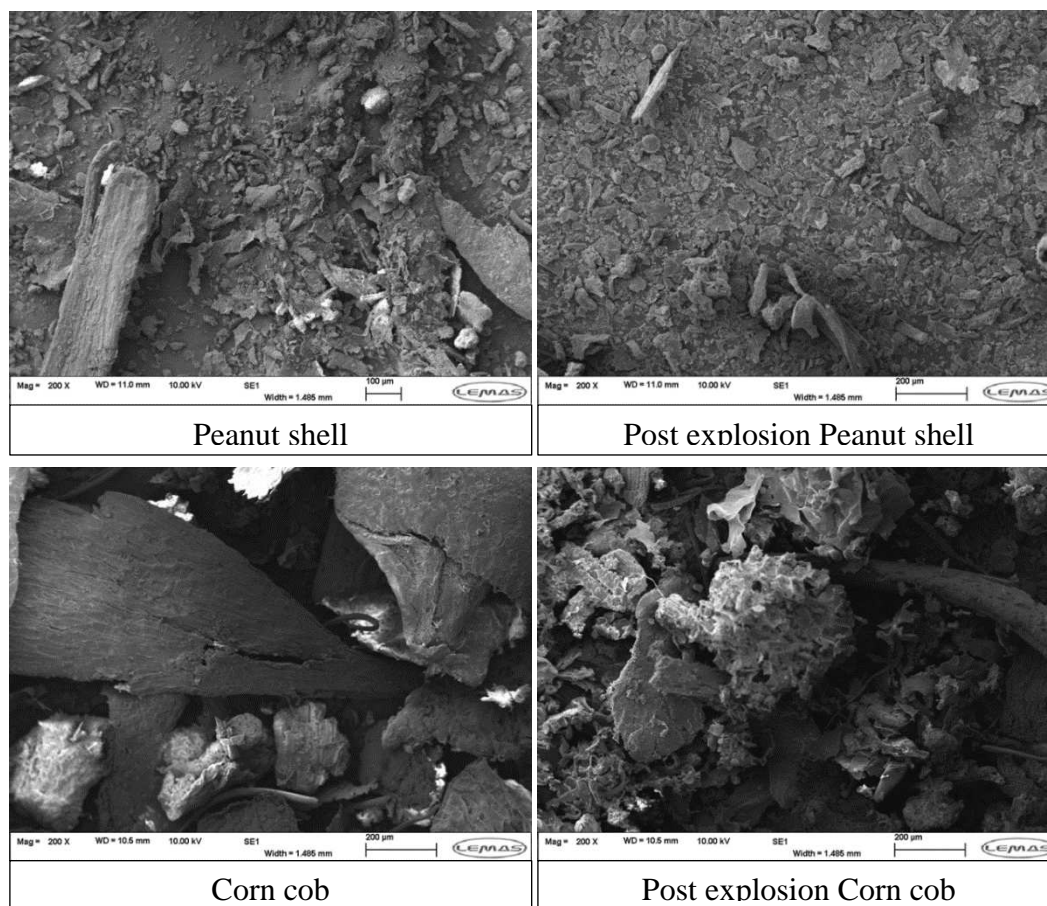
Fig. 4: Scanning Electron Microscopy of the post explosion residues in comparison to their respective samples

5. K_{st} and P_m/P_i Results

Fig. 5 shows two repeat tests of peanut shell were performed at a nominal concentration of 600 g/m^3. This shows a typical pressure time record and the measurement of dp/dt$_{max}$ by differentiation of the pressure time record. The repeatability of the test were good with 6.5% and 8% differences in P_m and K_{st} respectively. The K_{st}, P_m/P_i, S_T and S_u results as a function of Ø$_{burnt}$ are shown in Figs. 6-9 for the two biomass samples sieved to <500µm in comparison with two coals milled and sieved to <63µm. The coal samples had higher values of K_{st} mainly due to their much smaller particle size. Corn cob, CC, was more reactive than peanut shells, PS, with higher K_{st} and S_T, but the higher P_m/P_i for CC resulted in the maximum laminar burning velocities being lower for CC. The increase in reactivity by the change in K_{st} for CC relative to PS was much larger than that based on the turbulent flame speeds. This was not expected and could be due to the measurement being based on the reactivity close to peak pressure in the explosion, whereas the flame speeds were measured in the initial near constant pressure flame propagation. The pressure rise in the explosions are shown in Fig. 7 and show that despite the low reactivity of the coarse biomass, the pressure rise was high and would be completely destructive if it occurred inside an enclosure such as pellet silo or pulveriser mill or pellet manufacturing plant. Also a peak pressure close to the theoretical maximum for gas explosions indicated that complete combustion of the fine and coarse biomass had occurred.

Figs. 6 and 7 show that the minimum explosive concentration (MEC) for CC and PS were 0.62 and 0.85Ø$_{burnt}$ respectively. The lean limit for CC and PS were higher than the Kellingley
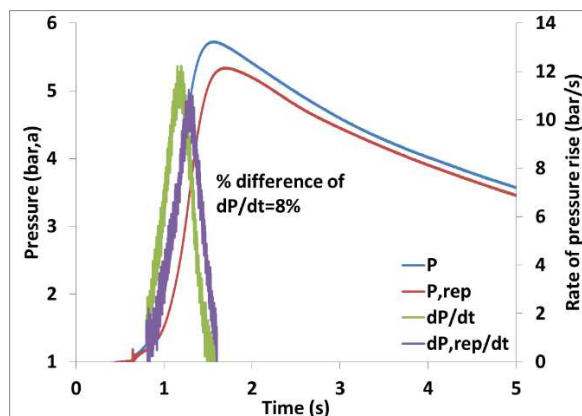
Fig. 3: Repeat tests of peanut shell for same concentration of 600 g/m³

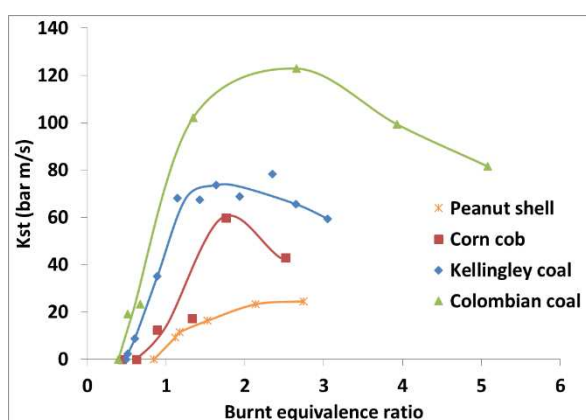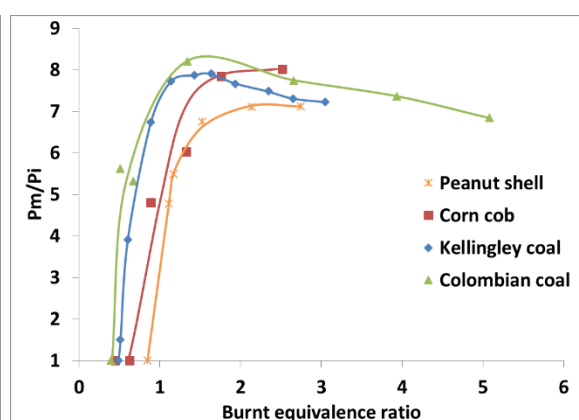**Fig. 6:** K_{st} v. $\varnothing_{burnt}$ for CC, PS and coal.

Fig. 7: P_m/P_i v. $\varnothing_{burnt}$ for CC, PS and coal.
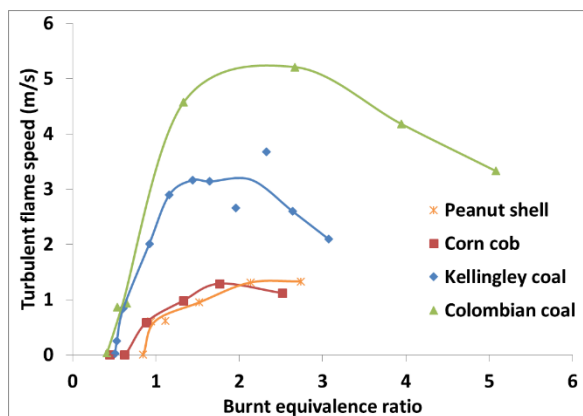
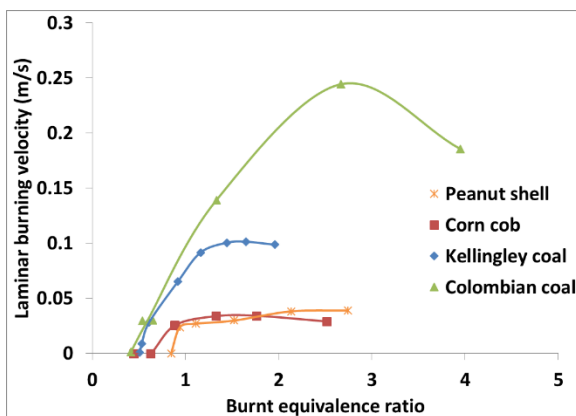**Fig. 8:** Turbulent flame speed, S_T, v. $\varnothing_{burnt}$.

Fig. 9: Laminar burning velocity v. $\varnothing_{burnt}$.

($\varnothing_{burnt}$=0.48) and Colombian coal samples ($\varnothing_{burnt}$=0.39). This difference was caused by the differences in the particles size after sieving to <63µm for the two coal samples and <500µm for the two biomass samples. Table 3 shows that PS were finer than CC and both had a very wide size distribution with 50% of the mass of size > 370µm for CC and 180µm for PS. CC due to higher volatiles and oxygen content was more reactive than the PS sample has lean minimum explosion concentration.

The pressure rise in Fig. 7 is driven by the temperature of the burnt gases and a maximum pressure ratio of 7 for PS indicates about 2100K as the burnt gas temperature. The peak

pressure for CC was higher at 8 indicating a burnt gas temperature of 2400K. This higher peak pressure for CC was unexpected as Table 2 shows that the GCV was much lower. For the two coal samples the Colombian coal had a 6% higher GCV than the Kellingley coal and there was a similarly higher peak pressure.

The mechanism for large size particles to react behind the flame front for rich mixtures, as discussed above, postulates that the large particles are gasified in the rich overall mixture but with a temperature generated by near stoichiometric combustion in the fine particles that burn first. The release of gasified gases, CO and hydrogen, by the large particles will cause the pressure to increase in the chamber, not due to flame temperature increases but due to gas volume addition. If a simple assumption is made that all the mass of CC injected after $\emptyset_{burnt}=1$ was converted into CO with no change in the temperature at stoichiometric, then it may be shown, using the C content of the biomass in Table 2, that the 5.5 pressure ratio at $\emptyset_{burnt} = 1$ would increase to 7 at $\emptyset_{burnt} = 2.5$. This is the pressure found for PS but for CC it was 8. This difference is probably due to the assumption of constant flame temperature, which is the temperature derived from the initial burning of the fines. As more mass is added, more fines occur and hence the temperature will rise and this is likely to account for the additional pressure ratio increase to 8 for the CC biomass.

6. Comparison with Previous Biomass Measurements of Flame Propagation

Table 5 compares the present work with previously published work using the same equipment as in the present work. Most of the previous work was for biomass milled and sieved to <63µm and this all showed a higher reactivity of the biomass due to the smaller size. Saeed et al. (2016) have investigated a mixed wood biomass (Spruce, pine, fir - SPF) that was milled and sieved to <1000µm and the results are very similar to the present work for agricultural waste biomass, the main difference was the lower ash in the wood sample. The present results show the CC and PS were slightly more reactive than the wood, in spite of the higher ash

Table 5: Comparison with Previous Biomass Measurements of Flame Propagation

Samples	$\emptyset_{peak}$ K_{st}	Peak Pm/Po	Peak K_{st} bar m/s	Peak S_T m/s	Peak S_u m/s	Refs.
Corn cob<500µm	1.8	8.0	60	1.3	0.03	This work
PS <500µm	2.7	7.1	25	1.3	0.04	This work
Wood SPF <1000µm	3.3	7.3	24	1.05	0.03	(Saeed 2016)
Bagasse<63µm	2.72	8.8	103	3.79	0.11	(Saeed 2015c)
Wheat Straw<63µm	1.57	8.5	82	3.0	0.13	(Saeed et al., 2015c)
Pistachio nut shells<63µm	2.4	9.3	82	3.7	0.27 Extrap.	(Sattar 2012a)
Walnut shells<63µm	2.8	9.4	98	5.1	0.24	(Sattar 2012a)
Pine 1<63µm	4.2	9.0	109	3.7	0.1	(Huéscar Medina 2013)
Spruce<63µm	1.9	8.8	81	3.4	0.09	(Huéscar Medina 2014b)
US Pine 2<63µm	2.5	9.0	105	4.5	0.11	(Huéscar Medina 2014a)

content. Saeed et al. (2016) showed that the prime correlator of the data in Table 4 was the particle size, which was different for each biomass even though the sieved size was the same.

7. Conclusions

Two agricultural waste biomass, corn cob (CC) and peanut shell (PS), were sourced from and milled in Pakistan and their flame propagation characteristics were determined. The milled samples were sieved to <500µm and the size distribution showed that PS had been milled finer than the CC. In spite of this the CC were found to be more reactive with a higher K_{st} of 60 compared with 25 for PS and comparable peak S_T of 1.3 in the initial constant pressure region. The peak pressure was also higher for CC indicating a higher flame temperature and this was in spite of the higher GCV for PS of 19.7 MJ/kg compared with 16.7 for CC. A model for the flame front of the explosion induced wind inducing a size separation with the fine particles (<100µm) propagating the flame and the coarse particles being gasified in the hot flame gases behind the flame front. This was shown to explain most of the observed results.

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References

Abbasi, T. & Abbasi, S. (2007). Dust explosions–Cases, causes, consequences, and control. Journal of Hazardous Materials, 140**:** 7-44.

Andrews, G. E. & Phylaktou, H. N. (2010). Explosion Safety. Handbook of Combustion. Edition type ed.: John Wiley and Sons, Inc.

Bridgwater, A., Meier, D. & Radlein, D. (1999). An overview of fast pyrolysis of biomass. Organic Geochemistry, 30**:** 1479-1493.

Eckhoff, R. K. (2003). Dust Explosions in the Process Industries: Identification, Assessment and Control of Dust Hazards. Gulf Professional Publishing, Amsterdam. 3rd ed.

Huéscar Medina, C., MacCoitir, B., Sattar, H., Slatter, D. J., Phylaktou, H. N., Andrews, G. E. & Gibbs, B. M. (2015). Comparison of the explosion characteristics and flame speeds of pulverised coals and biomass in the ISO standard 1m 3 dust explosion equipment. Fuel, 151**:** 91-101.

Huéscar Medina, C., Phylaktou, H. N., Andrews, G. E. & Gibbs, B. M. (2014a). Comparison of Explosion Characteristics of Torrefied and Raw Biomass. Proc. 22nd European Biomass Conference and Exhibition, Hamburg, Germany. 1025-1033.

Huéscar Medina, C., Phylaktou, H. N., Sattar, H., Andrews, G. E. & Gibbs, B. M. (2013). Torrefaction effects on the reactivity and explosibility of woody biomass. Proc. of the 7th International Seminar on Fire and Explosion Hazards, Providence, RI, USA.

Huéscar Medina, C., Sattar, H., Phylaktou, H. N., Andrews, G. E. & Gibbs, B. M. (2014b). Explosion reactivity characterisation of pulverised torrefied spruce wood. Journal of Loss Prevention in the Process Industries.

Indexmundi. (2015). Factbook [Online]. Available: http://www.indexmundi.com/pakistan/ [Accessed 1st April 2015].

Industrial-Fire-World. (2015). Incident logs [Online]. Available: https://fireworld.com/IncidentLogs.aspx [Accessed 10 November 2015].

Kaliyan, N. (2008). Densification of biomass. ProQuest.

Neves, D., Thunman, H., Matos, A., Tarelho, L. & Gómez-Barea, A. (2011). Characterization and prediction of biomass pyrolysis products. Progress in Energy and Combustion Science, 37**:** 611-630.

Saeed, M. A., Andrews, G. E., Phylaktou, H. N. & Gibbs, B. M. (2015a). Effect of steam exploded treatment on the reactivity of wood sample. Proceedings of the 8th Int. Conference on Sustainable Energy and Environmental Protection (SEEP2015), Paisley, Scotland, UK. 165 – 171.

Saeed, M. A., Andrews, G. E., Phylaktou, H. N. & Gibbs, B. M. (2015b). Global Kinetics of the Rate of Volatile Release from Biomasses in comparison to Coal. 1st Chemistry in Energy Conference (1st CEC). Edinburgh, UK.

Saeed, M. A., Andrews, G. E., Phylaktou, H. N., Slatter, D. J. F., Medina, C. H. & Gibbs, B. M. (2015c). Flame Propagation of Pulverised Biomass Crop Residues and their Explosion Characteristics 25th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS), Leeds, UK.

Saeed, M. A., Irshad, A., Sattar, H., Andrews, G. E., Phylaktou, H. N. & Gibbs, B. M. (2015d). Agricultural Waste Biomass Energy Potential in Pakistan. Proc. International Bioenergy Exhibition and Asian Bioenergy Conference, Shanghai.

Saeed, M. A., Medina, C. H., Andrews, G. E., Phylaktou, H. N., Slatter, D. & Gibbs, B. M. (2014). Agricultural waste pulverised biomass: MEC and flame speeds. Journal of Loss Prevention in the Process Industries, 36**:** 308-317.

Saeed, M. A., Slatter, D. J. F., Andrews, G. E., Phylaktou, H. N., Gibbs, B. M., Walton, R. & Niedzweicki, L. (2016). Flame Propagation of Coarse Wood Mixture: Raw and Torrified. In: EDS. J. CHAO, V. M., P. SUNDERLAND, F. TAMANINI AND J. TORERO., ed. Proc. 8th International Seminar on Fire and Explosion Hazards (ISFEH8), Heifei, China.: USTC Press.

Sami, M., Annamalai, K. & Wooldridge, M. (2001). Co-firing of coal and biomass fuel blends. Progress in energy and combustion science, 27**:** 171-214.

Sattar, H., Andrews, G. E., Phylaktou, H. N. & Gibbs, B. M. (2014). Turbulent Flames Speeds and Laminar Burning Velocities of Dusts using the ISO 1 m3 Dust Explosion Method. CHEMICAL ENGINEERING, 36.

Sattar, H., Phylaktou, H. N., Andrews, G. E. & Gibbs, B. M. (2012a). Explosions and Flame Propagation in Nut-shell Biomass Powders. Proc. of the IX International Seminar on Hazardous Process Materials and Industrial Explosions (IX ISHPMIE), Cracow.

Sattar, H., Slatter, D. J. F., Andrews, G. E., Gibbs, B. M. & Phylaktou, H. N. (2012b). Pulverised Biomass Explosions: Investigation of the Ultra Rich Mixtures that give Peak Reactivity. Proc. of the IX International Seminar on Hazardous Process Materials and Industrial Explosions (IX ISHPMIE), Cracow.

Slatter., D. J. F., Andrews, G. E., Huéscar Medina, C., Phylaktou, H. N., Gibbs, B. M. & Sattar, H. (2014). Biomass explosion residue analysis. Proc. Tenth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions (XISHPMIE), Bergen, Norway.

Tumuluru, J. S., Sokhansanj, S., Wright, C. T., Boardman, R. D. & Yancey, N. A. (2011). A review on biomass classification and composition, co-firing issues and pretreatment methods. Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting. Citeseer: 2053-2083.

Wang, J., Yan, Q., Zhao, J., Wang, Z., Huang, J., Gao, S., Song, S. & Fang, Y. (2014). Fast co-pyrolysis of coal and biomass in a fluidized-bed reactor. Journal of Thermal Analysis and Calorimetry, 118**:** 1663-1673.