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# Agricultural waste pulverised biomass: Lean Flammability and Flame Speed as a Measure of Reactivity

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## Abstract

There is very little information on the combustion properties of pulverised biomass, particularly for agricultural wastes. This makes burner design and optimization difficult and also has implications on fire and explosion hazard protection, both in storage, milling and particle transport to burner. A modified Hartmann dust explosion tube was employed to determine the Minimum Explosible Concentration (MEC) and the flame speed for three Pakistani agricultural wastes: bagasse, rice husk and wheat straw. The MEC was influenced by the particle size distribution and there was a strong linear correlation between the MEC and the sum of the ash and moisture content of these and other biomasses. Comparison of the results was made with more conventional pulverized biomass. Peak flame speeds were approximately 2.5 m/s. The lean limits for these pulverised agricultural waste biomasses were comparable to pulverised wood but much leaner than those for coal and hydrocarbon fuels, which indicate that these biomasses are highly reactive.

Keywords: *agricultural waste, MEC, pulverised biomass, flame speeds.*

## 1. Introduction

Concerns over global warming together with the cost of fossil fuels are leading to the wide scale adoption of solid biomass as a renewable source of energy. Pakistan is an agricultural country which has multiple crops produced each year due to the favorable climate. Urban areas of Pakistan generate over 20 Mtpa (Megatonnes per annum) of solid wastes, about 82 Mtpa of crop residue and over 365 Mtpa of animal manure (Pakistan-Renewable-Energy-Society, 2013). The major crops include wheat, rice, cotton, maize and sugarcane (Agriculture-Census, 2010). These crops produce large quantities of residues and disposal of these residues requires land and has a cost. Some of these crop residues are utilized for burning, using inefficient stoves in rural areas of the country. This renewable energy fuel can be applied more widely for electric power generation, rather than just for cooking as at present. Overall Pakistan has more than 100 billion tonnes of food crops produced per annum with associated non-food residues of around 150 billion tonnes per annum, which currently have little useful end-use.

A rough estimate reveals that the annual production of crop residues is enough to support the country's annual electric power requirements, assuming a 30% thermal efficiency conversion in the electrical generation plant. Also it is economically a feasible option for an agricultural

country like Pakistan to utilize its local resources for the production of electricity. Pakistan currently has an energy crisis due to its over-reliance on oil for electric power generation, with no oil resources of its own. This has led to higher electricity costs and blackouts on a frequent basis. Its waste agricultural biomass resources are advocated as a potential low cost solution to this problem, although it will require considerable investment in steam power generation from new biomass steam generation plant. These plants will have the capability to co-fire with coal of which Pakistan does have significant resources that are not currently exploited as they have only recently been discovered. The agricultural waste resources of Pakistan could provide the fuel for a series of 50MW steam power stations based on agricultural waste in a 50 km radius from the plant. This avoids excessive transportation costs and reduces the need to process the fuel prior to transport. It is a power production model that would be suitable for the Pakistani economy and population needs.

In more developed economies with an existing infrastructure of GW sized coal fire plants, conversion of these to burn pulverized biomass, normally pine wood, has been undertaken. These large scale plants today do not pulverise the biomass but import pellets where the biomass has already been dried, pulverised and compressed at the country of origin of the biomass and then shipped to the country of end use. At the power station the pellets are broken back into a pulverized form with some secondary pulverisation. This puts up the cost of the biomass, but enables it to be used in pellet form in existing coal pulverization units, often in co-firing mode with coal. The problem of converting biomass into a more useable form has led to the development of second generation biomass processing, using gasification of the biomass and combustion of the gas in a gas turbine for electric power generation. Alternatively, biomass can be torrefied to produce a 'biocoal' that can be milled using the same equipment as for coal (Huéscar Medina et al., 2013b). All of these second generation fuels increase the cost and the upstream processing and CO<sub>2</sub> emissions. None of these second generation biofuels are appropriate for Pakistan, as there is no infrastructure of large scale coal fired power generation. Pakistan does have a widespread infrastructure for milling agricultural materials into powders and all the present samples were milled in these local mills in Pakistan.

The use of biomass in pulverized form gives the most efficient combustion with the least excess air for low CO<sub>2</sub> emissions. The use of pulverised biomass as a fuel in power generation is relatively new and started with co-firing with coal. However, there are now large scale 100% pulverized biomass combustion steam generation plant. There is a dearth of data on the fundamental combustion properties of pulverised biomass, in terms of data on flame propagation rates that are necessary for burner design. Also there are fundamental safety problems for which there is a lack of data on the Minimum Explosible Concentrations (MEC), the explosibility indices  $K_{st}=(dp/dt_{max}/V^{1/3})$ , flame speeds and peak pressures. Flash-back of biomass in the supply tubes to the burner is a problem due to its enhanced reactivity relative to coal, which this work will demonstrate. Also biomass dust explosions can occur in biomass storage silos, in the transfer lines from the pulverisers to the burners and in the pulveriser. The frequency with which this is occurring in biomass plants, as given in the examples below, shows that there is a lack of basic safety data on pulverized biomass as well as a lack of appreciation of its high reactivity.

At least one dust fire or explosion is reported every day in biomass plants (Abbasi and Abbasi, 2007). Some recent incidents related to biomass dust explosions are given below as examples.

- ***Tandil Argentina grain silo agricultural plant [January 28, 2013]***  
An explosion occurred in a grain silo at an agricultural plant that killed 1 and injured another (Industrial-Fire-World, 2013).
- ***Fire and then explosion at Jaffrey, N.H., manufacturing plant, New England Wood Pellet LLC [October, 2011 ]***  
It took 100 fire fighters and 15 hours to put down the fire. The company had to pay fine of \$100,000 (Fitzgerald and Bowser, 2011).
- ***Explosion at the RWE's 750,000 ton wood pellet factory, Georgia, USA [June, 2011]***  
An overheated roller/bearing assembly in a pelletizer sparked the blast at the factory (Renewables-International-Magazine, 2011).

The operation of a burner involves the mixing of the dust cloud with air in close to stoichiometric proportions. For a flame to stabilise, the burner air and dust flow has to be greater than the burning velocity, else there will be a flashback that could reach the mill. However, if the burner flow velocity is too high then there may be flame lift off and the generation of unstable flames, which in extreme circumstances can result in the boiler enclosed space undergoing a biomass dust air explosion. All industrial boiler flames of this type are turbulent, irrespective of the fuel, but pulverized biomass requires turbulent flow for the particles to remain suspended. This also applies to the basic laboratory investigation techniques, which differ in the way that turbulent clouds of dust and air are formed. In addition there are explosion hazards in biomass storage areas such as silos and on the conveyor belts that transfer biomass to mills and from mills to burners.

Pulverised biomass flames propagate by thermal transfer of heat by conduction and radiation from the reaction zone into the advancing unburned biomass dust air turbulent cloud. The biomass powder undergoes de-volatilisation as the particle moves towards the reaction zone and biomass powders release typically 80% of their mass as volatile material when they are heated to around 300°C, as will be shown for the present agricultural biomass. In comparison, coal releases much less volatiles, at typically 30% by mass and the assumption that these are hydrocarbons is often made. It is shown in the analysis of the present biomass that the much larger volatile emissions from biomass heating cannot be hydrocarbons and must be a mixture of CO, hydrogen and some hydrocarbons. It is also possible that under the rapid heating in a flame front more of the biomass is converted into volatiles. Sattar et al. (2012a, b) have found no evidence for char to remain after biomass dust explosions in the ISO 1 m<sup>3</sup> explosion vessel and this indicates that all the biomass is converted into volatile products during the rapid heating in flame front.

Heating of particles in the flame front depends on the particle size and on the flame speeds, which control the residence time. The mass of a particle increases as the cube of its size, however when heated this may not matter as the release of volatiles decreases the mass possibly shatters the particles into smaller particles. Slatter et al. (2013) showed, using the present equipment, that pine wood particles sieved to be between 300 and 500 µm could still explode, but only for very rich mixtures. These rich mixtures are encountered in biomass pulverization mills. Liquid sprays will not explode at this size and the only explanation that large biomass particles will explode is that sufficient volatiles are released on heating to enable a flame to propagate. Only rich mixtures burn as most of the mass is not heated sufficiently to release the volatiles. It will be shown in the present work for agricultural residue biomass that the same influence of particle size occurs as for the previous work on pine wood dusts. Palmer (1973) showed that if the volatiles in a dust were less than 12.5%

then the dust was non-explosive if the rest of the dust was inert. He also showed that fine dusts release more volatiles due to higher surface area and smaller mass per particle.

A lump of coal of mass 1kg contains no hazard when suspending into a 1m<sup>3</sup> vessel but explodes when dispersed in air after pulverization to a size of <100µm (Hertzberg et al., 1987). There is a certain size (about 30 µm) below which the flame propagation is independent of the size of the particles (Cashdollar, 2000). Hertzberg et al. (1982) conducted experiments using Pocahontas coal, Pittsburg coal and Polyethylene dust in an 8L chamber and showed that below a minimum size, the minimum explosive concentration became independent to the size of the dust particles and increased with the particle size until a size was reached that did not ignite. Cashdollar (1996) used a 20L vessel to investigate the effect of particle size distribution on the explosion severity. The conclusion was that fine particles pose a greater hazard than the coarser particles due to ease of release of volatiles when exposed to an ignition source. Their work showed that Pittsburg coal particles greater than 200µm were not explosible but a mixture of fine particles with the coarse were explosible. Wilen et al. (1999) used a 20L and a 1m<sup>3</sup> test vessel to investigate the effect of agricultural residue's particle size on the explosibility. They found that larger size biomass particles could still explode whereas similar sized coal particles could not. Spanish pine and rapeseed straws (median sizes 247µm and 318µm respectively) still ignited with a MEC of 83.1 and 174.5 g/m<sup>3</sup> respectively. This shows that biomass particles were more reactive than the coal particles due to the higher evolution of volatiles at lower temperatures in the reaction zone.

Pilao et al. (2006) used cork dust of varying size fractions of median sizes 47µm, 71µm, 128µm, 222µm, 366µm and 438µm. It was found that all the fractions of particle size less than 180µm had the same MEC. The cork dust particles still propagated a flame at median size 438µm. Larger particles of biomass are reactive in comparison to coal due to higher volatile yields. Huéscar Medina et al. (2013a) tested different fractions of biomass and torrefied biomass on the modified Hartmann tube of size ranges: <38µm, 38-75µm, 75-150µm and 150-300µm and demonstrated ignition of all the size fractions. Slatter et al. (2013) used pine wood of different size fractions and showed that the highest sized fraction of biomass (300µm - 500µm) could still propagate a flame. This showed that fines were not necessary for coarse particles to propagate a flame, but that the coarse particles were more reactive if mixed with fines.

Two measurements of mixture reactivity are used in the present work: the minimum explosion concentration, MEC, or the lean explosibility limit, LEL; and the turbulent flame speed under standard turbulence conditions. The MEC or LEL for reactive gases such as hydrogen is an equivalence ratio ( $\emptyset$ ) of 0.13 and for hydrocarbons such as methane and propane it is 0.45. It is well known that hydrogen is more reactive than methane and propane and hence the MEC can be used as an indicator of reactivity for biomass dusts.

The flame speed of a dust depends on a number of factors: composition of the dust (humidity and ash), size of the dust particles, turbulence of the gas resulting solid-gas suspension and the elemental composition on a dry ash free basis (daf) which determines the stoichiometric concentration,  $\emptyset$ . Sattar et al. (2012a,b) showed that the maximum flame speed occurred at  $\emptyset$  of about 2 compared with  $\emptyset$  of 1.05 for hydrocarbon gas/air mixtures. The reason for this significant difference is unclear, but it occurs for all HCO type dusts (Eckhoff, 2003), but has not been realized in the dust explosion literature, as the dust concentrations have not been typically expressed in terms of  $\emptyset$ , but only as g/m<sup>3</sup> (Andrews & Phylaktou, 2010). The effect of size, water and ash content on the minimum explosive concentration was investigated in this work together with the measurement of the flame speed for a wide range of  $\emptyset$ . This enabled the  $\emptyset$  for the maximum reactivity to be determined.

## 2. Experimental techniques

The separation of the samples into different sized fractions was performed on a sieve shaker. The “as received” samples were separated into different sized fractions of 300-500  $\mu\text{m}$ , 150-300  $\mu\text{m}$ , 75-150  $\mu\text{m}$ , 63-75  $\mu\text{m}$  and less than 63  $\mu\text{m}$  prior to chemical characterisation. The elemental analysis of biomass crop residues was carried out using a Flash 2000 Thermo Scientific Analyser. It consists of a single reactor with temperature of 1800°C for the detection of Carbon, Hydrogen, Nitrogen and Sulphur (CHNS) with O found by subtracting the mass of CHNS from the original mass. At this extreme temperature, the material is converted into gas comprising of carbon dioxide, water, nitric oxides and sulphur oxides. These combustion products are separated by a chromatographic column and detected using a Thermal Conductivity Detector (TCD).

Proximate analysis was carried out using a Shimadzu TGA-50 thermo gravimetric analyzer. It consisted of a mass balance attached to a ceramic sample pan in a furnace. It records the weight loss with time and temperature from which may be determined the moisture, volatiles, fixed carbon and ash contents. The operating procedure was:

1. The sample was heated in nitrogen from ambient temperature to 110°C at a rate of 10°C/min and maintained at 110°C for 10 minutes so as to completely dry the sample.
2. The temperature was increased to 910°C at a rate of 25°C/min and held for 10 min to stabilise the weight after the volatile loss.
3. Air was introduced at 910°C to react with any fixed carbon. The mass loss was the fixed carbon content. The remaining material left after this is inert ash.

The ash in the biomass samples was analysed using XRF analysis with the weighed sample placed in a furnace at 1250°C which oxidises all material other than the ash. The XRF technique utilizes an X-ray beam to remove the inner orbital electron of the specific element that makes the element unstable. A specific photon energy of specific intensity is released when the outer orbital electron is shifted to the inner orbit to fill the gap of missing electron. The intensity of photon and number of photon of specific fluorescent radiation are utilised to detect and quantify the elements in the ash.

The biomass crop residues were tested on the same modified Hartmann tube, shown in Fig. 1, as used by Huéscar Medina et al. (2012, 2013a,b) and Slatter et al. (2013). The Hartmann explosion tube is the most appropriate approach for biomass dust MEC measurement as the dust is placed inside the vessel and dispersed with a blast of air. The standard ISO 1m<sup>3</sup> vessel cannot easily measure the MEC of biomass due to the difficulties in injecting fast enough pulverized woody biomass through the delivery tubes and the injector. The Hartmann Perspex tube has 1 litre volume with 61mm internal diameter and is 322mm long. The continuous 4J spark arc was located 110mm above the dust injector. This was activated prior to the initiation of the dust injection. A pressure transducer was added at the top of the tube just below the aluminium foil exit vent cover. Confinement for the initial explosion was provided by covering the top end of the tube with Aluminium foil of 0.020mm thickness, fixed with a locking ring.

With the air blast injection into the Hartmann tube the aluminium foil does not break until there is an overpressure in excess of 0.55 bar, as shown in Fig. 2. The air injection was from a 0.06 litre external container pressurized to 7 bar, which gives consistent repeatable MEC measurements (Huéscar Medina et al., 2012, 2013a,b).



Figure 1: Modified Hartmann tube

The air injection generates a pressure rise of 0.35 bar as shown in Fig. 2. The dust is placed inside the vessel at the bottom of the tube so that the incoming compressed air is directed onto the dust where a cloud of dust/air forms. The pressure transducer records the pressure rise as shown in Fig. 2. The flame arrival time at the three thermocouples is shown in Fig. 3 to demonstrate a uniform flame movement up the tube.

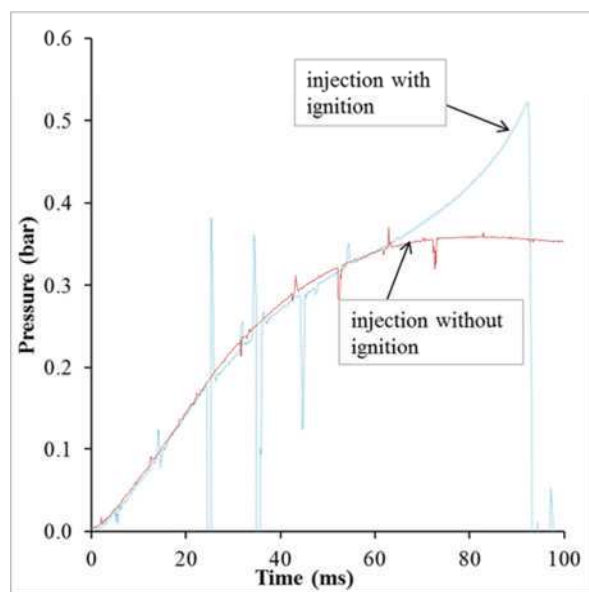


Figure 2: An explosion pressure record

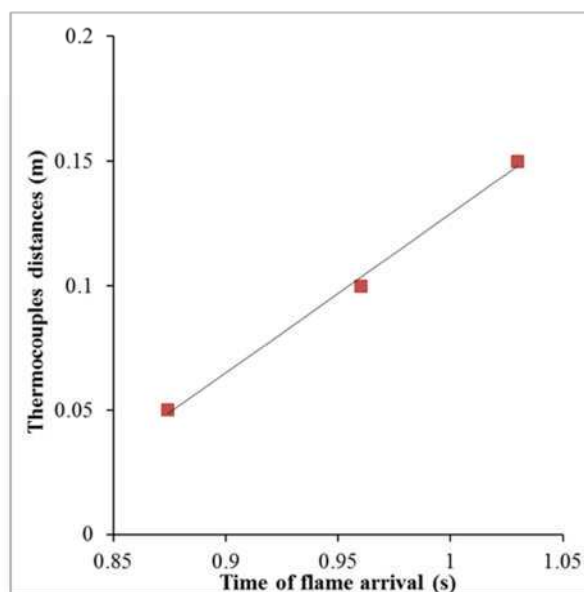


Figure 3: Example of flame speed measurement

### 3. Elemental and Proximate analysis

The elemental analysis of the three pulverized agricultural waste materials used in the present work are shown in Table 1 which also includes a comparison of the composition of the sieved  $<63\mu\text{m}$  samples. Table 1 also includes comparison with other biomass and HCO dusts analysed by the authors. The biomass composition is shown in Fig. 4 as H/C v. O/C with a comparison with other biomass and coal. This shows that wheat straw, rice husks and pistachio nut shell dusts are all chemically similar and bagasse is significantly different.

Table 1: Elemental and Proximate analysis of as received and small size fraction samples in comparison with other biomass and HCO dusts.

| Biomass               | C (%) | H (%) | N (%) | S (%) | O (%) | H <sub>2</sub> O (%) | VM (%) | FC (%) | Ash (%) | CV (MJ/kg) | Stoich. A/F (g/g) | Stoich. Actual Mass (g/m <sup>3</sup> ) |
|-----------------------|-------|-------|-------|-------|-------|----------------------|--------|--------|---------|------------|-------------------|---|
| Rice Husk (as rec.)   | 37.1  | 4.7   | 0.8   | 0.02  | 31.8  | 7.7                  | 62.3   | 12.2   | 17.9    | 15.2       | 6.15              | 262.2                                   |
| Rice Husk (<63µm)     | 30.4  | 4.2   | 1     | 0.2   | 26.4  | 6.56                 | 51.7   | 10.5   | 31.2    | 14         | 6.24              | 309                                     |
| Bagasse (as rec.)     | 40.4  | 5.3   | 0.9   | 0.07  | 26.0  | 7.2                  | 67.1   | 5.6    | 20.1    | 15.6       | 7.46              | 221.3                                   |
| Bagasse (<63µm)       | 35.6  | 4.6   | 0.8   | 0.1   | 28.7  | 6.85                 | 60.5   | 9.3    | 23.4    | 15.05      | 6.45              | 266.7                                   |
| Wheat Straw (as rec.) | 35.7  | 4.5   | 1.0   | 0.05  | 29.2  | 6.8                  | 60.7   | 9.7    | 22.8    | 14.5       | 6.35              | 268.4                                   |
| Wheat Straw (<63µm)   | 23    | 2.96  | 0.46  | 0.03  | 20.3  | 3.98                 | 38.7   | 8.08   | 49.2    | 13.93      | 6.03              | 425                                     |
| Lycopodium            | 64.3  | 8.9   | 1.9   | 0.0   | 19.2  | 1.6                  | 89.2   | 5.1    | 4.1     | 29.6       | 10.4              | 122.3                                   |
| Corn flour            | 37.8  | 6.3   | 0.1   | 0.0   | 40.5  | 11.6                 | 77.8   | 6.8    | 3.8     | 16.4       | 5.64              | 251.5                                   |
| Walnut Shells         | 47    | 6     | 0.5   | 0.1   | 35.2  | 4.95                 | 74.6   | 14.2   | 6.3     | 18.75      | 6.75              | 200.3                                   |
| Pistachio nut shells  | 44    | 5.6   | 2.3   | 0     | 37.1  | 2.7                  | 78.4   | 10.7   | 8.3     | 17.8       | 6.22              | 216.8                                   |
| Pine wood             | 50    | 5.7   | 1.7   | 0     | 33.9  | 4.27                 | 80.2   | 11     | 4.4     | 19.2       | 6.98              | 188.2                                   |

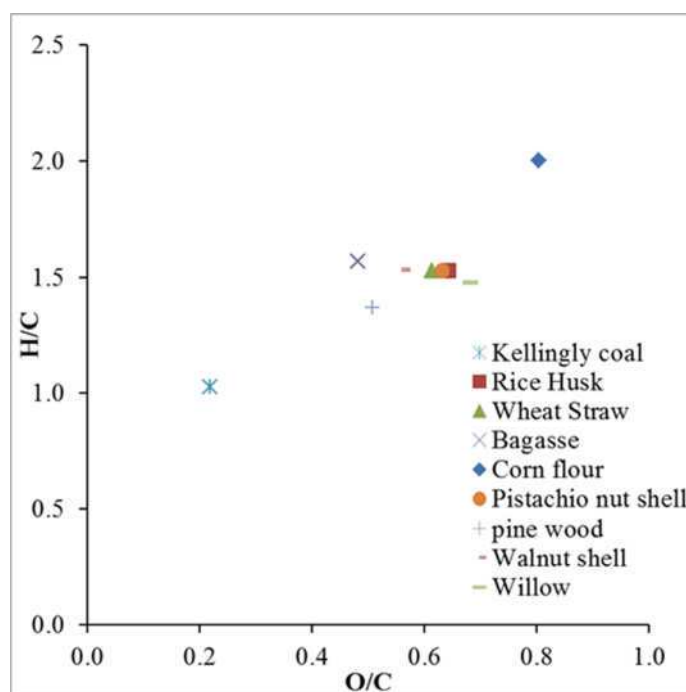


Figure 4: H/C against O/C molar ratios for biomass and coal samples

The TGA and elemental analysis may be used together to deduce the composition of the volatiles. The fixed carbon is deducted from the elemental carbon mass and then a carbon,



hydrogen and oxygen balance carried out to give the measured volatile content. If we assume the composition of the volatiles to be CO, CH<sub>4</sub> and H<sub>2</sub> then a mass balance can give the theoretical proportions of these gases. For bagasse this gives a volatile gas composition by mass of 68.9% CO, 30.8% CH<sub>4</sub> and 0.3% H<sub>2</sub>; for rice husks it is 90.6% CO, 2.3% CH<sub>4</sub> and 7% H<sub>2</sub>; for wheat straw it is 85.7% CO, 9% CH<sub>4</sub> and 5% H<sub>2</sub>. The main difference is that on this basis bagasse has more CH<sub>4</sub> in the volatiles than for the other biomass dusts.

Table 1 shows that the as received composition of the coarse samples of rice husks and wheat straw were very similar with a similar stoichiometric A/F of about 6.3, which is very similar to pistachio nut shells. Bagasse was significantly different with a stoichiometric A/F by mass of 7.5. Table 1 shows that the stoichiometric A/F by mass is quite variable for biomass and this has to be taken into account in the design of burners and in the explosion safety case, as explosion hazards are relative to the lean flammability limit and hence the concentration that is safe varies with the composition of the fuel. The agricultural waste biomasses were all significantly higher in ash than for pine wood or nut dusts and this would make their application in furnaces quite difficult due to the problem of enhanced slag formation. In the present work the concern over the high ash content of the biomass was also investigated over its action on the combustion and explosions properties of the biomass

Table 1 shows that sieving the agricultural waste material to <63µm had a very significant influence on the elemental composition. For all three agricultural waste biomass the finer sample was always higher in ash than the original sample. This was particularly significant for rice husks and wheat straw. Littlejohn (1966) found a similar phenomenon with coal samples, milling finer increased the ash content from about 10% for 250µm to 35% for 10µm. He showed that the finer particles had discrete mineral matter in their content and that milling preferentially mills the mineral matter finer than coal and hence it forms a larger proportion of the mass. This was because in air swept mills the mineral particles are retained longer due to their greater density and this produces finer mineral matter particles than for the base coal. It is likely that a similar phenomenon is occurring with biomass milling. However, it is difficult to explain why this effect was so small for bagasse.

An example of the thermogravimetric analysis of a milled biomass sample is shown in Fig. 5, which illustrates how the water, volatile, carbon and ash content were determined. Table 1 shows that all three samples of biomass had a high volatile content but not as high as for pine wood and nut shell biomass. The reason for this is associated with the higher ash content. When the temperature range over which the volatiles are released are compared, as in Fig. 6, all the agricultural biomass were similar with 70% of volatiles released between 300 and 400°C. Sieving the samples did not change the temperature range over which biomass particles release volatiles as shown in Fig. 7, which supports that conclusion that finer particles have more ash rather than more volatiles or different volatiles.

#### 4. Ash characterisation

The XRF characterisation of the ash is shown in Table 2. The greatest constituent was silica which varied between 48 and 87% and would give rise to a slagging problem at high temperature. Some of the other ash constituents such as potassium would give rise to corrosion problems in boiler tubes.

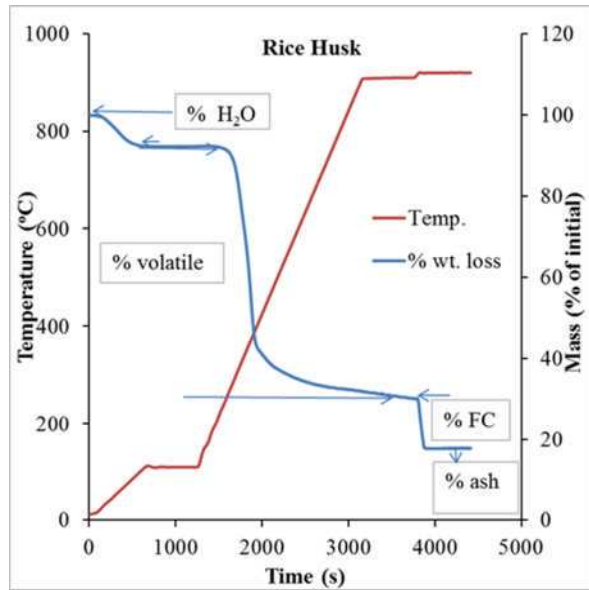


Figure 5: Typical TGA record for rice husk

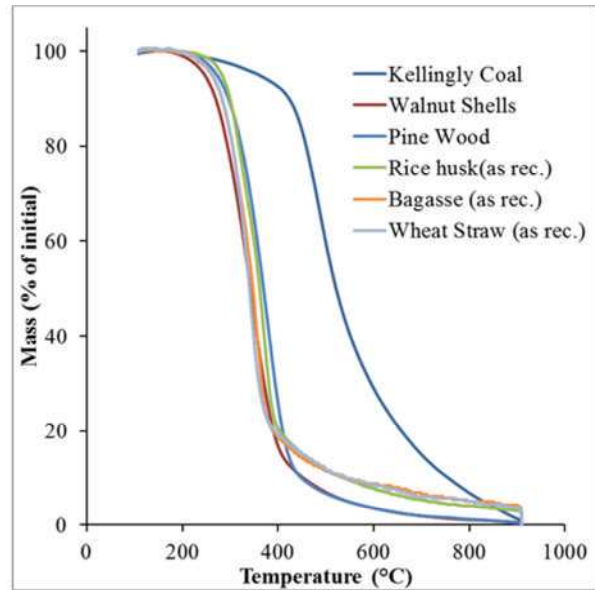


Figure 6: Mass loss for different biomasses over the temperature range for volatile release.

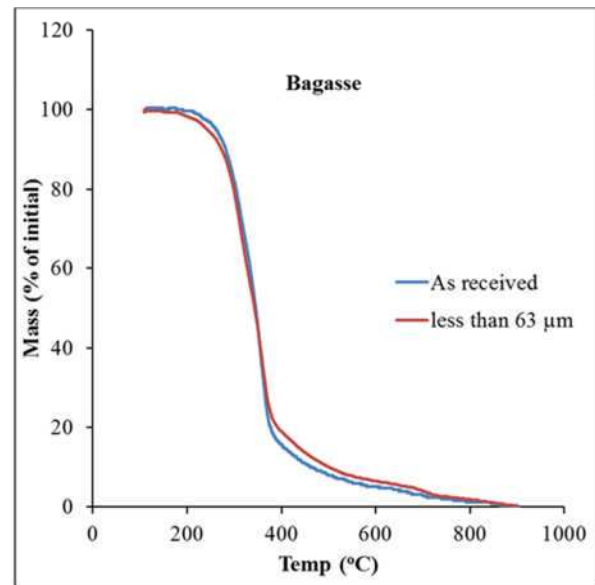
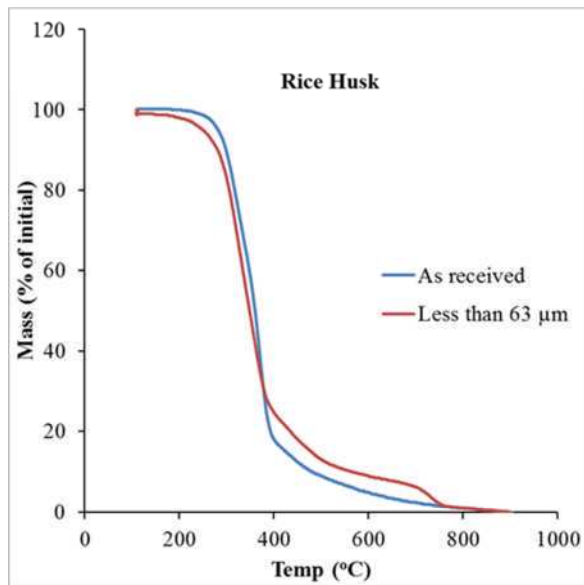


Figure 7: Volatile mass loss as a function of temperature for rice husks and bagasse with the influence of sieving to 63 $\mu$ m.

The ash content also acts as a flame inhibiting source through the action of the ash as a heat sink, which will lower the flame temperature and lower the reactivity. These biomass crop residues should be processed before adoption as electric power plant fuels. One way of reducing the ash content is to wash with the clean water or apply some acid treatment to dissolve or absorb the ash contents in the liquid medium. Washing with water can remove up to 70% of the alkali metals in the biomass feedstocks (Fahmi et al., 2007).

Table 2: Ash analysis of as received samples by XRF analysis (wt. %)

|                   | Al <sub>2</sub> O <sub>3</sub> | BaO  | CaO | Fe <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | MgO | MnO | P <sub>2</sub> O <sub>5</sub> | SiO <sub>2</sub> | SrO  | TiO <sub>2</sub> | Others |
|-------------------|--------------------------------|------|-----|--------------------------------|------------------|-----|-----|-------------------------------|------------------|------|------------------|--------|
| WS <sub>ash</sub> | 10.5                           | 0.04 | 5.4 | 0.6                            | 9.5              | 2.2 | 0.2 | 0.7                           | 59               | 0.05 | 0.9              | 11     |
| RH <sub>ash</sub> | 1.3                            | 0    | 2.3 | 0.9                            | 2.1              | 0.4 | 0   | 0.6                           | 87               | 0.01 | 0.01             | 5      |
| B <sub>ash</sub>  | 9.1                            | 0.1  | 9.4 | 3.5                            | 5.2              | 3.1 | 0.6 | 1.7                           | 48               | 0.2  | 0.7              | 19     |

## 5. Rate of pressure rise and flame speed measurements as a function of $\emptyset$

The reactivity, in terms of the maximum rate of pressure rise before the vent bursts and the flame speed, for each biomass is shown in Fig. 8 as a function of the equivalence ratio  $\emptyset$  on a dry ash free basis (daf). Both methods of determining the reactivity show a reasonable correlation as shown in Fig. 9 for all the particle size ranges investigated. A critical feature of burner operation and of safety assessment is to know the worst case most reactive mixture  $\emptyset$ , as explosion protection measures require them to be designed for the most reactive mixture. Thus determining and understanding the mixture condition where this occurs is important and has been neglected in the literature.

Figure 8 shows that both methods of determining the reactivity give a peak reactivity at about the same  $\emptyset_{\text{daf}}$ . For wheat straw dusts with particle size  $<63\mu\text{m}$  and  $63-75\mu\text{m}$  the peak reactivity was  $\emptyset_{\text{daf}}=1.4$  and for rice husk dusts of the same size range the peak reactivity was  $\emptyset_{\text{daf}}=1.5$ , which is very similar. Similarly for bagasse of the same size range the peak reactivity was  $\emptyset_{\text{daf}}=1.25$ . Most hydrocarbon gases have a peak reactivity at  $\emptyset=1.05$ . For rice husk and wheat straw dusts the reactivity was higher for  $63-75\mu\text{m}$  dusts and this was because of the increase in ash content as the dust was milled finer. For bagasse this did not occur and the  $<63\mu\text{m}$  dust was the most reactive, probably due to the lower ash content of this fine dust.

Although there was a reasonable correlation between the rate of pressure rise prior to the vent bursting and the flame speed for a given biomass, the correlation between different biomass in terms of the relative reactivity was not good. The rate of pressure rise showed that rice husk dust and bagasse dust had similar peak reactivity, which was roughly twice that of wheat straw dust. The peak flame speeds for rice husk and bagasse dusts were 2.5 m/s compared with 2.0 m/s for wheat straw. The pressure rise approach is considered to be a better reactivity measurement as it measures the mean mass burning rate and hence takes into account the shape of the flame. The flame speed measurements are made on the centreline of the vessel and this may not be the mean flame speed.

There are no previous measurements to our knowledge on this type of agricultural waste biomass with  $<63\mu\text{m}$  particle size, but the present results indicate that there could be fire and explosion hazards associated with these agricultural waste materials due to their high volatile content that enhances their reactivity. Table 1 shows that the main reason that wheat straw could be less reactive is that for the fine powders the volatile matter is very low at 39% compared with 52% and 61% for rice husks and bagasse respectively. Wheat straw also had the highest ash content in the  $<63\mu\text{m}$  dust and this will reduce the dust reactivity.

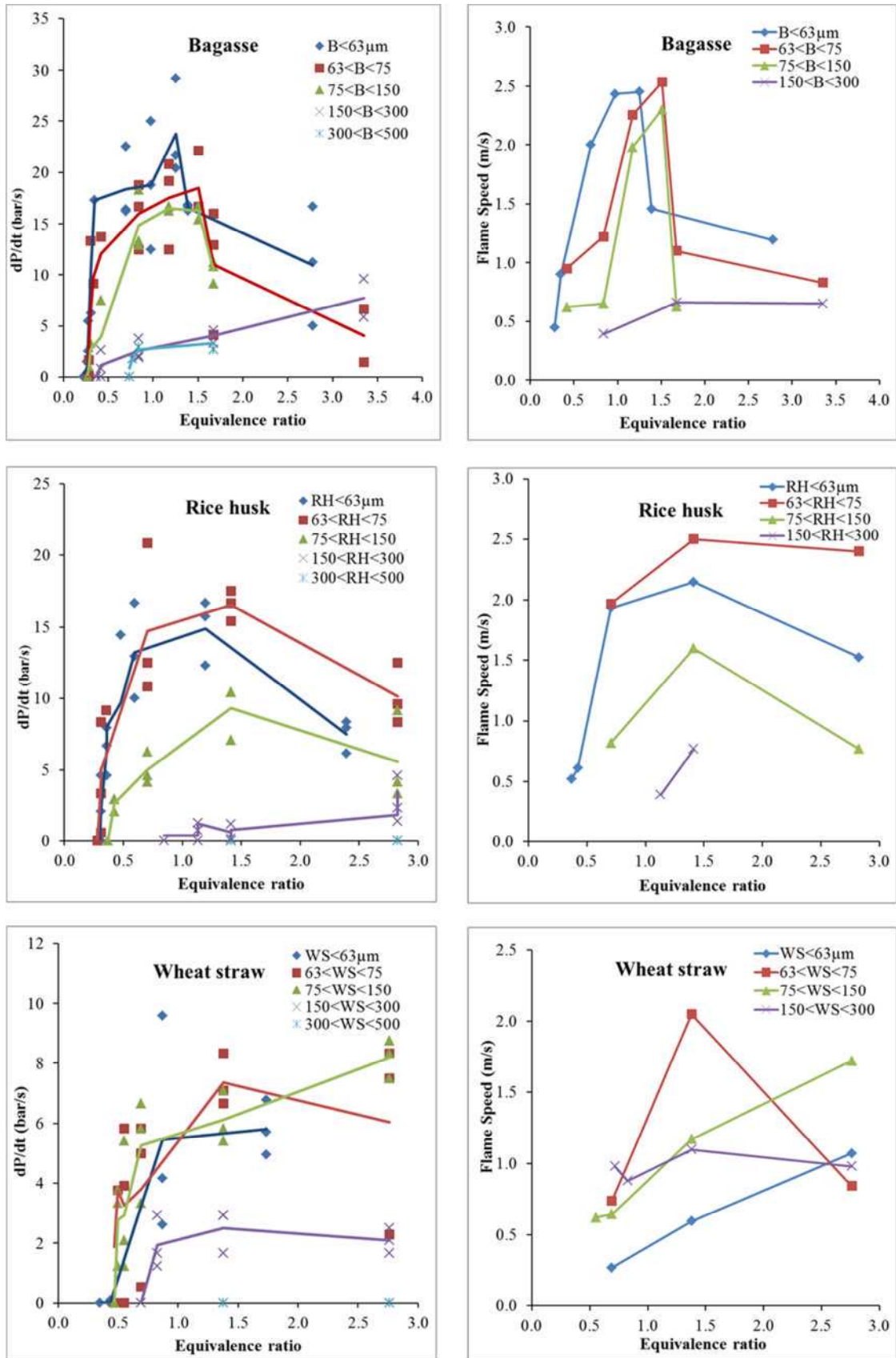


Figure 8: Rates of pressure rise and flame speeds as a function of daf. equivalence ratio and particle size

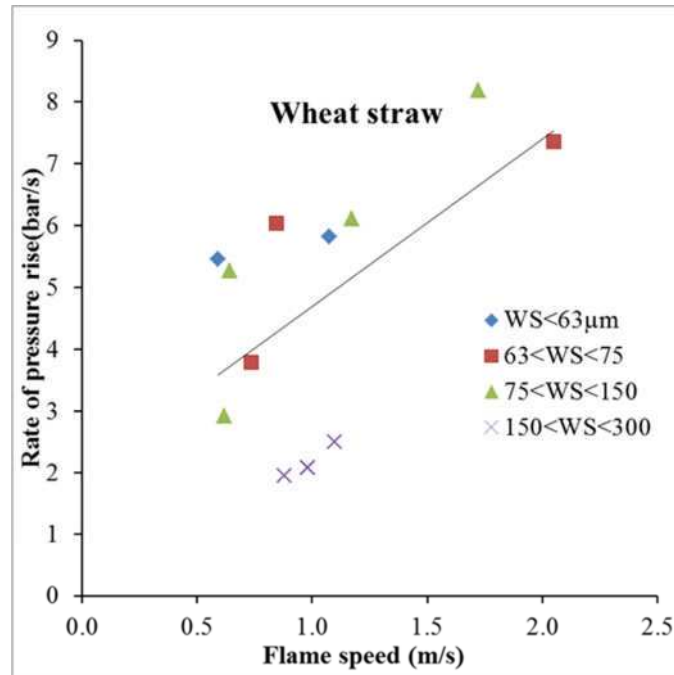


Figure 9: Correlation of flame speed and rate of pressure rise for wheat straw dust for various size ranges

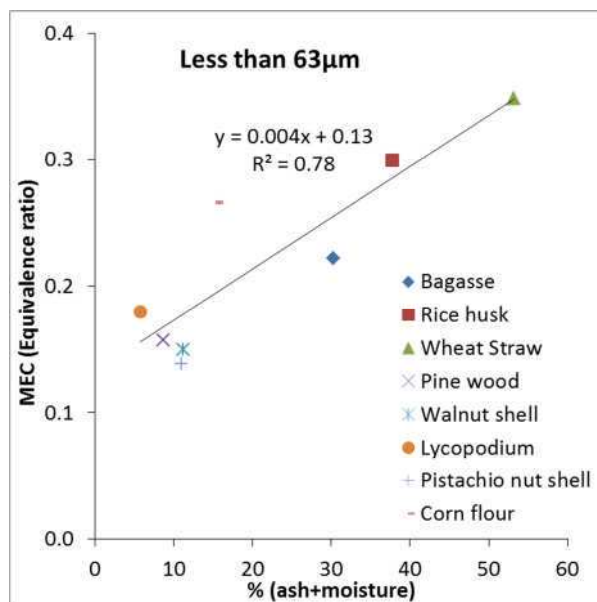


Figure 10: MEC as a function of ash + moisture content of the biomass

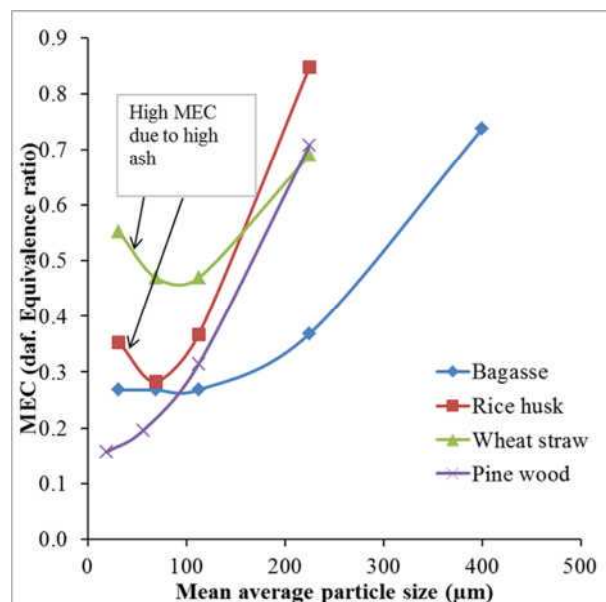


Figure 11: Comparison of the MEC vs. particle size for the present three biomass dusts with that of pine wood (Slatter et al., 2013)

## 6. MEC results and the influence of particle size and ash+moisture

The MEC results were determined from the limiting mixture that would give a pressure rise of 100mbar over the air injection pressure, this is the analogous condition used for MEC measurement in the ISO 1 m<sup>3</sup>. Also the MEC limit was determined from the mixture where a flame propagated 100mm for agreement with the gas flammability measurements in Europe. The two methods of measuring the MEC were in good agreement. The MEC results for <63μm biomass dusts are shown in Fig.10 as a function of the sum of the water and ash

content. In addition to the present agricultural biomass results other measurements made by the authors on this equipment have been added for comparison (Slatter et al., 2013; Huéscar Medina et al., 2012, 2013a). Fig. 10 shows a very good correlation between the MEC and the ash plus water content proportion by mass. The reason for this relationship is that water and ash act as inerts that reduce the dust flame temperature and thus reduce its reactivity. These results show that wheat straw has the richest MEC and is thus the least reactive dust, due to the presence of the highest ash and water content.

The MEC results are shown as a function of particle size in Fig. 11, where they are compared with the results of Slatter et al. (2013) for milled pine wood dusts. The data points are plotted at the middle of the size range. The results show that the present biomass had little change in the MEC until particles were bigger than 150 $\mu\text{m}$  and then increased rapidly. However, for all biomass relatively coarse biomass would explode, but were not very reactive as shown in Fig. 8. Nevertheless, this makes for a real explosion hazard in biomass mills as the mixtures there are relatively rich.

## 7. Conclusion

The modified Hartmann equipment can be used to accurately determine the MEC and the concentration that has highest reactivity. It can also be used to determine the relative reactivity of different biomass dusts. Agricultural waste biomass has a high ash and water content and this reduces the mixture reactivity and increases the MEC due to the action of the ash and water as inert heat sinks.

The MEC correlates well with the mass fraction of the sum of ash and water content for biomass. The most reactive mixture occurs for  $\text{Ø}=1.5$  for rice husks, 1.25 for bagasse and 1.4 for wheat straw. Of the three biomasses investigated wheat straw was the least reactive in terms of the rate of pressure rise and the MEC. This was because it had the highest ash content in the <63 $\mu\text{m}$  size range biomass. Milling the biomass concentrated the ash in the finer particles and this resulted in the 63-75 $\mu\text{m}$  size range being the most reactive, except for bagasse, which had the least increase in ash in the finer dust.

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