



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/89061/>

Version: Accepted Version

Proceedings Paper:

Saeed, MA, Andrews, GG, Phylaktou, HN et al. (2015) Flame Propagation of Pulverised Biomass Crop Residues and their Explosion Characteristics. In: Radulescu, MI, (ed.) Proceedings of 25th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS). 25th International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS), 02-07 Aug 2015, University of Leeds, Leeds, UK. ICDERS.

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Flame Propagation of Pulverised Biomass Crop Residues and their Explosion Characteristics

Muhammad Azam Saeed, Gordon E. Andrews, Herodotos N. Phylaktou, David Slatter, Clara Huéscar Medina and Bernard Gibbs
Energy Research Institute,
School of Chemical and Process Engineering, University of Leeds, LS2 9JT, UK

1 Abstract

Pulverised agricultural crop residues were investigated using the ISO 1 m³ turbulent explosion vessel. This was modified to enable the spherical flame propagation flame speed and the heat release rate in MW/m² to be determined. From the turbulent flame speed, the laminar flame speed and laminar burning velocity and global heat release, MW/m², were determined. In addition the equipment was used to determine the biomass explosibility, K_{st} ($= dP/dt_{max} V^{1/3}$), and the minimum explosion concentration (MEC). Two Pakistani crop residues bagasse (B) and wheat straw (WS) were investigated. Particle size distribution, elemental and proximate analysis and surface morphology for the raw powders and for their post explosion residues were carried out. It was found that these crop residues have explosibility characteristics comparable to wood biomass powders. MEC values as low as equivalence ratios of 0.18 to 0.3 were found which were lower than for gaseous hydrocarbons, but similar to other measurements for biomass using the Hartmann explosibility equipment. Peak turbulent flame speeds were measured at 3-4 m/s. There was a significant post explosion residue of unburned material which was shown to have an increase in char content relative to the raw biomass, while the volatile content was reduced. The BET surface area of the post explosion residue of bagasse was higher than that of the wheat straw residue, showing a higher release of volatiles for bagasse with a more porous char residue in the burnout indicating higher reactivity. These crop residues are a viable renewable fuel for existing coal power plants or as a basis for a new generation of small scale steam power generators in Pakistan.

2 Introduction

Worldwide interest is growing in biomass crop residues as an energy source, due to their short rotation cycle, ease of availability and low cost [1]. For Pakistan crop residues could be the sustainable basis for 40%+ of the existing electrical power consumption. However, there is little fundamental information on the combustion and explosion properties of pulverised agricultural biomass and this work aimed to provide such data. Crop residues contain higher ash than wood, which can be reduced by water washing by 60-80% [2]. Further reduction can be achieved with acid or base washing depending upon the type and amount of the minerals in the ash content. Biomass crop residues can be employed separately or in combination with coal to reduce fossil fuel CO₂ emissions [3, 4]. The application of pulverised crop residue dusts in power plants requires the assessment of the

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

3 Experimental Methodology

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

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

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

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

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

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

Biomass	C daf. (%)	H daf. (%)	N daf. (%)	S daf. (%)	O daf. (%)	H ₂ O (%)	VM (%)	FC (%)	Ash (%)	CV (MJ/kg)	Stoich. A/F (g/g)	Stoich. (g/m ³)
Bagasse	55.6	7.3	1.3	0.1	35.7	7.2	67.1	5.6	20.1	15.6	7.5	221.3
Wheat Straw	50.6	6.4	1.4	0.07	41.5	6.8	60.7	9.7	22.8	14.5	6.4	268.4

4 Experimental Results

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

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

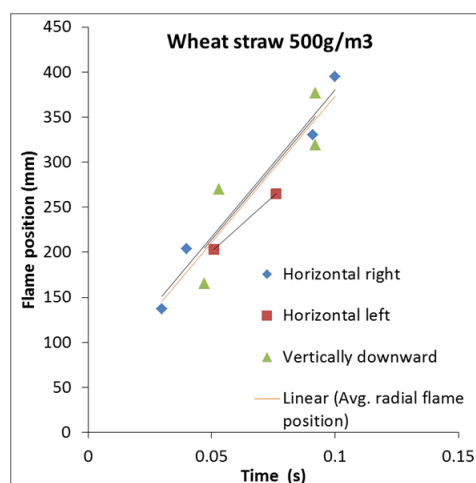


Figure 1. Example of the flame arrival time as a function of distance, the flame speed is the slope of the line.

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

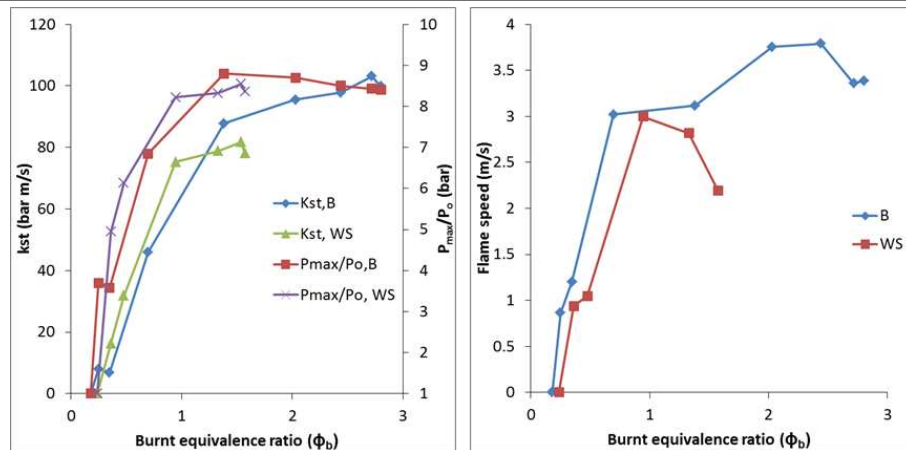


Figure 2. Comparison of K_{st} , P_{max}/P_o and flame speeds of crop residue dusts Bagasse and Wheat straw against burnt equivalence ratio

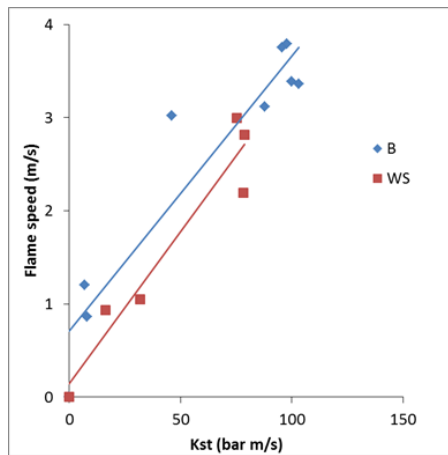


Figure 3. A correlation of flame speed vs. K_{st} for crop residue dusts

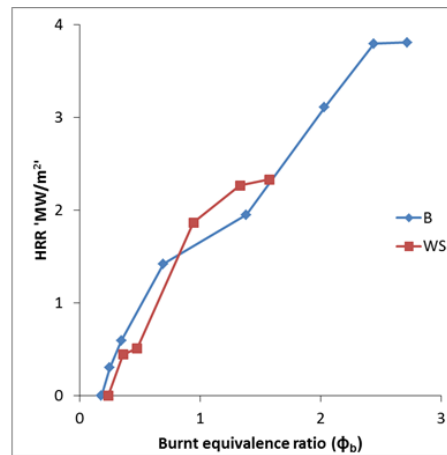


Figure 4. Heat release rate as a function of burnt equivalence ratio for crop residue dusts

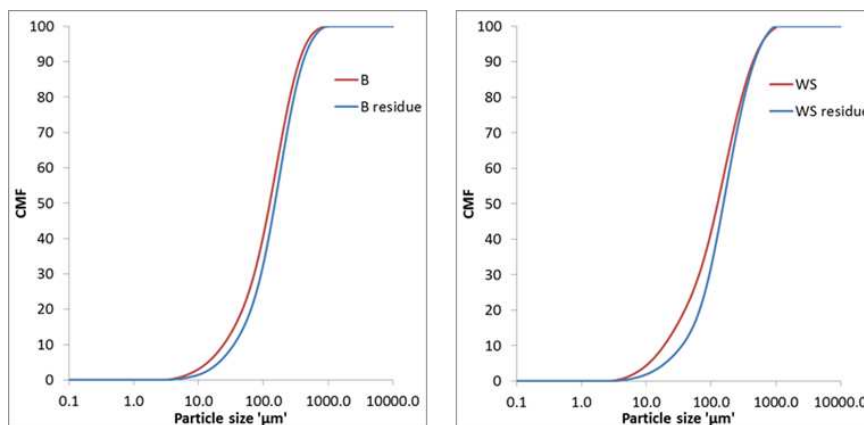


Figure 5. PSD of selected crops and their post explosion residues. Left: Bagasse dust. Right: Wheat straw dust

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

$$HRR = \frac{(S_{ft} \cdot \rho_u \cdot GCV)}{E(1 + A/F)}$$

where S_{ft} = Turbulent flame speed (m/s), ρ_u = density of air (Kg/m^3), GCV = Gross calorific value (MJ/Kg), E = Expansion factor (P_{max}/P_o) and A/F = Air to fuel ratio by mass.

The results are shown in Fig. 4 which shows that the HRR increases with ϕ and continues to increase in the rich region. This is mainly driven by the flame speed measurements in Fig. 2 which continue to go faster for rich mixtures. There is no decrease in the flame speed or HRR in the rich region as would occur for rich gaseous mixtures. The peak heat release rate for the biomass fuels was 3.8 MW/m^2 for bagasse and 2.3 MW/m^2 for wheat straw. These are well in the range of existing pulverised coal furnaces where $2\text{-}5 \text{ MW/m}^2$ is typical [16]. Thus it may be concluded that the turbulence conditions and turbulence flame propagation rates in the ISO 1 m^3 vessel are comparable with those for conventional pulverised coal plants.

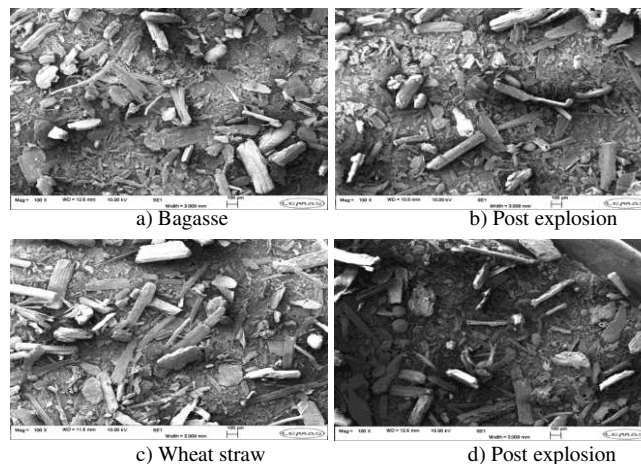


Figure 6. Surface morphology comparison of crop samples and their post explosion residues

The MEC were determined after correcting for actual burnt concentration. It was found that bagasse dust had a lean limit burnt ϕ of 0.18 whereas wheat straw dust had $\phi = 0.24$. This is a further indication that bagasse was more reactive than wheat straw. These lean limits are in good agreement with other woody biomass dusts and are much lower than for the coal and hydrocarbon dusts [9, 11].

The particle size distribution (PSD) of the raw biomass samples were lower than their post explosion residues as shown in Fig. 5. This might be due to swelling of the particle due to evolution of volatiles in the combustion. BET surface area and surface morphology analysis showed a more porous structure for bagasse than wheat straw for the raw material and for the post explosion residues. The ash content of wheat straw resulted in the formation of cenospheres from silica in the ash. The residues were mainly the original material, but with some charring of part of the material. Previous work by the authors has shown that the residue occurs because the explosion induced expansion wind ahead of the flame carried dust with it into the wall where it was compressed against the wall. The flame impinges on this layer and chars the outer surface. However, most of the layer remains unburned and is original dust that did not participate in the explosion.

5 Conclusions

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

References

- [1] McKendry P. 2002 Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*.83:37-46.
- [2] Fahmi R, Bridgwater AV, Darvell LI, Jones JM, Yates N, Thain S, et al. 2007 The effect of alkali metals on combustion and pyrolysis of Lolium and Festuca grasses, switchgrass and willow. *Fuel*.86:1560-9.
- [3] Nuamah A, Malmgren A, Riley G, Lester E. 2012 Biomass Co-Firing.55-73.
- [4] Nussbaumer T. 2003 Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. *Energy & Fuels*.17:1510-21.
- [5] Palmer KN. 1973. Dust explosions and fires: Chapman and Hall London;.
- [6] Eckhoff RK. 2003. Dust Explosions in the Process Industries: Identification, Assessment and Control of Dust Hazards. 3rd ed. Amsterdam: Gulf Professional Publishing.
- [7] Hertzberg M, Cashdollar KL. 1987. Introduction to dust explosions
- [8] Saeed M.A. HMC, Andrews G.E., Phylaktou H.N., Slatter D and Gibbs B.M. 2014. Agricultural waste pulverised biomass: MEC and flame speeds Tenth International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions Bergen, Norway, 10-14 June 2014. Bergen, Norway.
- [9] Andrews, G.E. and Phylaktou, H.N., "Explosion Safety". pp. 377 – 413. Handbook of Combustion Vol. 1: Fundamentals and Safety. Edited by Maximillian Lackner, Franz Winter and Avinash K. Agrawal Copyright 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim ISBN: 978-3-527-32449-1. DOI: 10.1002/9783527628148.hoc016.
- [10] Sattar, H., Phylaktou, H., Andrews, G.E. and Gibbs, B.M. 'Explosions and Flame Propagation in Nut-shell Biomass Powders' Proc. of the IX International Seminar on Hazardous Process Materials and Industrial Explosions (IX ISHPMIE), Krakow, 2012.
- [11] Huescar Medina, C., Phylaktou, H.N., Andrews, G.E. and Gibbs, B.M. Torrefaction Effects on the Reactivity and Explosibility of Woody Biomass. *Proceedings of the Seventh International Seminar on Fire and Explosion Hazards (ISFEH7)*, pp.878-885, 2013. Research Publishing. doi:10.3850/978-981-07-5936-0_13-11.
- [12] Sattar H, Huéscar Medina C, Phylaktou HN, Andrews GE, Gibbs BM. 2012. Calibration of a 10L volume dust holding pot for the 1m³ standard vessel, for use in low-bulk-density biomass explosibility testing. Proc of the IX International Seminar on Hazardous Process Materials and Industrial Explosions (IX ISHPMIE). Cracow.
- [13] Sattar, H., Andrews, G.E., Phylaktou, H.N, and Gibbs, B.M., 2014, Turbulent flame speeds and laminar burning velocities of dusts using the ISO 1 m³ dust explosion method. *Chemical Engineering Transactions*, 36, 157-162 DOI: 10.3303/CET1436027. Also Presented at the 6th International Conference on Safety & Environment in Process & Power Industry (CISAP6) Bologna, Italy, 13-16 April, 2014.
- [14] Sattar, H., Slatter, D.J.F., Andrews, G.E., Gibbs, B.M and Phylaktou, H.N., '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), Krakow, 2012.
- [15] Huescar-Medina, C., Andrews, G.E., Phylaktou, H.N. and Gibbs, B.M., Comparison of explosion characteristics of Columbian coal and Kellingley Coal. *Proceedings of the 10th European Conference on Coal Research and its Applications*, University of Hull, 2014. Also in: *Fuel*. doi:10.1016/j.fuel.2015.01.009.
- [16] Basu P. 2006. Combustion and gasification in fluidized beds: CRC press.