Article:

Saeed, MA, Farooq, M, Andrews, GE et al. (2 more authors) (2019) Ignition sensitivity of different compositional wood pellets and particle size dependence. Journal of Environmental Management, 232. pp. 789-795. ISSN 0301-4797

https://doi.org/10.1016/j.jenvman.2018.11.122

Journal of Environmental Management 232:789-795 15 Feb 2019

Ignition sensitivity of different compositional wood pellets and particle size dependence

M. Azam Saeed[a,c], M. Farooq[b,d,*], Gordon E. Andrews[a], Herodotos N. Phylaktou[a],

Bernard M. Gibbs[a]

[a] School of Chemical and Process Engineering, University of Leeds, LS2 9JT, UK

[b] Institute of Mechanical, Process & Energy Engineering, Heriot-Watt University, UK

[c] Department of Chemical and Polymer Engineering, University of Engineering and Technology, Lahore, Faisalabad Campus, 54000, Pakistan

[d] Department of Mechanical Engineering, University of Engineering and Technology, Lahore, KSK Campus, 54000, Pakistan

Abstract

Partial or complete substitution of coal with renewable biomass like wood is a sustainable and effective solution to reduce the CO_2 emissions in the atmosphere. Utilization of these woods in the form of compact pellets facilitates in its handling and transportation with higher energy density. However, for electric power generation the pellets are broken up into their constituent milled finer particles for burning as a pulverised biomass flame. There is a dust fire/explosibility hazard in the process handling facilities such as in storage, conveying and milling. In the present work, four commercial pellets from UK suppliers were investigated and each pellet sample was split into three size ranges <63µm, 63-500µm and <500µm. The flame propagation characteristics and their lean flammability limit for each pulverised pellet was determined using modified Hartmann dust explosion tube. It was found that the fine particles intensify the explosibility risk of the dust due to fast volatile release rate. Comparison was also made between particle size distribution (PSD) of the finer fractions (<63µm) of wood samples in comparison to crop residue samples. Scanning Electron Microscope (SEM) imaging showed higher PSD for wood finer fraction. Results showed that the ash + moisture content had a stronger effect on wood samples than on agricultural residue's samples. The results showed that the explosibility characteristics of the pellets industry's feed-stocks was variable and dependent on the pellet composition and this needs to be taken into account in explosion protection and in utilising the pellets in the main pulverised biomass combustion.

Keywords

Renewable; Pulverised biomass; Combustion; Emissions; Flammability limit

1. Introduction

Fast depletion of the fossil fuels and its worst environmental effects are not found to be economically and environmentally competitive. Renewable and sustainable source of energy are promoting all over the world due to net zero emission of carbon credits (Schobert, 2013, Demirbaş, 2001, Vassilev et al., 2010). The wood pellet industry is growing for energy applications (Wilson et al., 2011, Badger and Fransham, 2006, Boman et al., 2003, Kumar et al., 2003, Tillman, 2000, Saeed et al., 2017). A huge stock of wood pellets is used as fuel for boilers. These wood pellets generate some fine dusts in their handling due to wearing and tearing of the pellets. The handing and transportation of these wood pellets requires the assessments of the fire and explosibility hazards associated with the fine dust particles. Size of the dusts for fire/explosion is dominant parameter that reflects the severity of the consequence. Higher the size of the dust particles, lower the explosibility and vice versa (Eckhoff, 2003, Palmer, 1973).

Flame propagation in the dust explosion is mainly due to the fine particles. The instantaneous burning of the coarse dust cloud was not observed for coal for size<180µm (Cashdollar, 1996, Hertzberg et al., 1982). However for some biomass, coarse particles of size upto <500µm were found to take part in the propagation of flame but the severity of the dust explosion was leaner in comparison to the fine dusts flame propagation. The inherent oxygen contents and higher release of volatiles in the low temperature range were believed to be the main driving force for the severity of the dust explosion.

A lump of coal of mass 1kg contains no hazard when suspending into a 1m^3 vessel but explodes when dispersed in air after pulverization to a size of <100µm (Hertzberg and Cashdollar, 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 (1982) conducted experiments using Pocahontas coal, Pittsburg coal and Polyethylene dust in an 8L chamber. It was found 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 instantaneously (Hertzberg et al., 1982). Cashdollar (1996) used a 20L vessel to investigate the effect of particle size distribution on the explosion severity (Cashdollar, 1996). The conclusion was drawn that fine particles pose a greater hazard than the coarser particles due to ease of release of volatiles when exposed to an ignition source. Also the Pittsburg coal particles greater than 200µm were not explosible. Wilen et al. (1999) used a 20L and a 1m^3 test vessels to investigate the effect of agricultural residue's particle size on the explosibility (Wilén et al., 1999). It was 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 (Minimum explosive concentration) of 83.1 and 174.5 g/m^3 respectively. This shows that biomass particles were more reactive than the coal particles due to the higher evolution of volatiles at lower temperatures.

Pilao et al. (2006) used cork dust of varying size fractions of median sizes 47µm, 71µm, 128µm, 222µm, 366µm and 438µm (Pilão et al., 2006). 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 (Pilão et al., 2006). Larger particles of biomass are reactive in comparison to coal due to higher volatile yields and fast volatiles rate at lower temperature (Saeed et al., 2016a). Huéscar Medina et al. (2013) tested different fractions of biomass and torrefied biomass on the modified Hartmann tube of size ranges: <38µm, 38-75µm, 75-150µm and 150-300µm (Huéscar Medina et al., 2013) 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 (Slatter. et al., 2013). 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. The author used the same modified Hartmann (Huéscar Medina et al., 2013) to find the explosibility characteristics of crop residues of different size ranges <63, 63-75, 75-150,150-300 and 300-500µm and experienced the mild ignition of the coarse size fraction (300-500µm) for crop residues having lower ash and moisture contents (Saeed et al., 2015). The results showed that finer fraction was more sensitive to ignition however for crop residues like wheat straw and rice husk having higher ash+moisture contents, the lean limits were found to be higher than the next coarse fraction (63-75). The results revealed that milling of the crop residues having higher ash contents shift the higher ash fraction to the finer size range fraction that counter balance the enhancement of the reactivity due to small size fraction.

This work utilized the conventional wood pellets feed-stocks of three different size ranges <63, 63-500 and <500µm to study the role of fine and coarse particles in the dust flame propagation. The results will help for safe handling and exploitation of wood mixtures for power generation.

1. Experimental techniques

All of these wood pellets were milled using SM 100 cutting mill to less than 500µm size. Then they were sieved to three size range fractions <63, 63-500 and <500µm using the analytical sieve shaker 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℃ 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 consists of a mass balance attached to a ceramic sample pan in a furnace. It records the weight loss against time and temperature that was used to determine the percentage moisture, volatiles, fixed carbon and ash contents. The operating procedure was:

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

The wood pellet dust samples were tested on the same modified Hartmann tube, shown in Fig. 1, as used by Huéscar Medina et al. (2012, 2013) (Huéscar Medina et al., 2012, Huéscar Medina et al., 2013), Slatter et al. (2013) (Slatter. et al., 2013) and Saeed et al. (2014) (Saeed et al., 2015). 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 $1m^3$ 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 inside 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 Aluminum foil exit vent cover. Confinement for the initial explosion was provided by covering the top end of the tube with Aluminum 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, Huéscar Medina et al., 2013).

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. These flame speeds are based on center point and is not the representative of the flame propagation due to the average mass burning. Therefore, the rate of pressure rise is represented for reactivity as it is more appropriate parameter of reactivity showing the flame propagation results based on average mass burning.

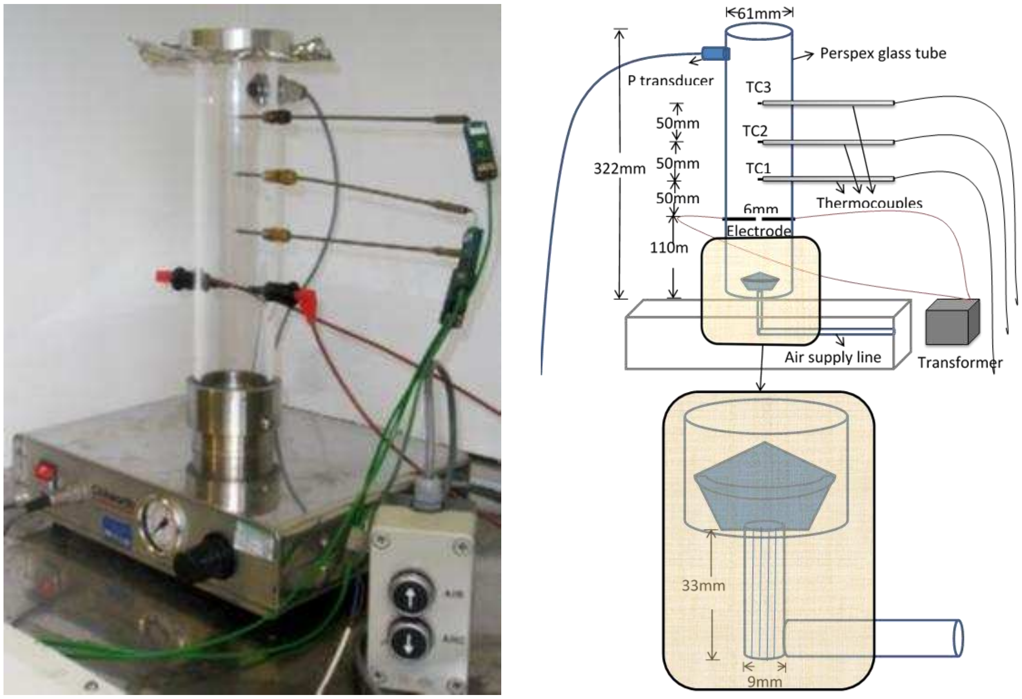


Figure 1: Modified Hartmann dust explosion tube with schematic diagram

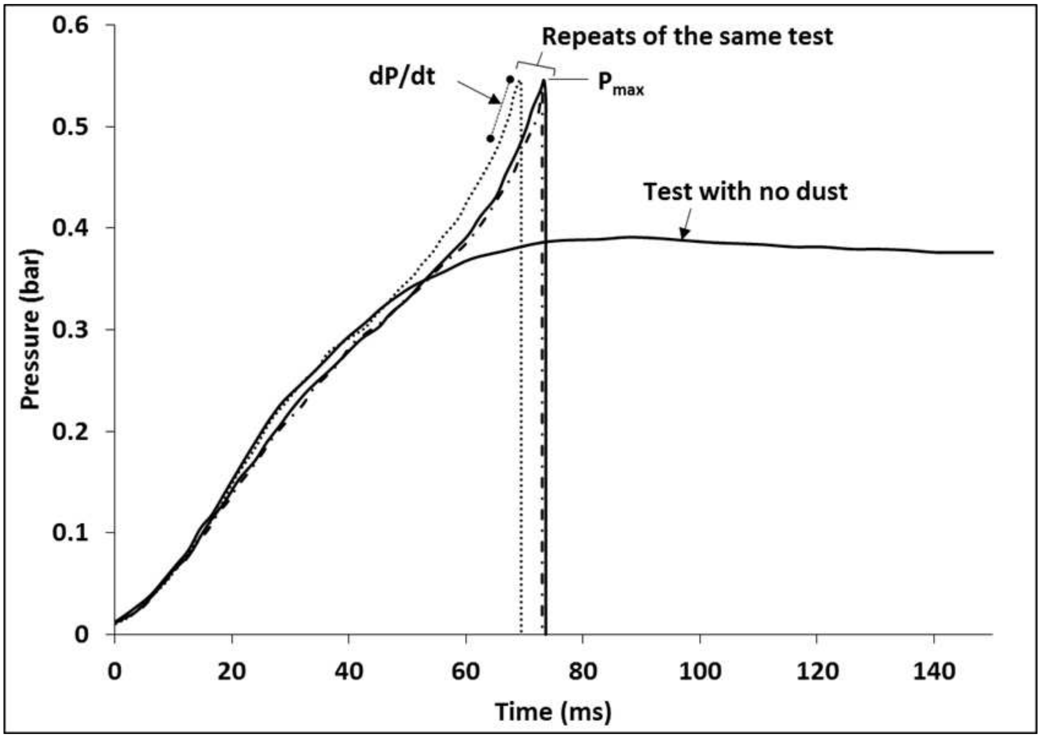


Figure 2: Repeat tests explosion pressure record in comparison to no dust explosion

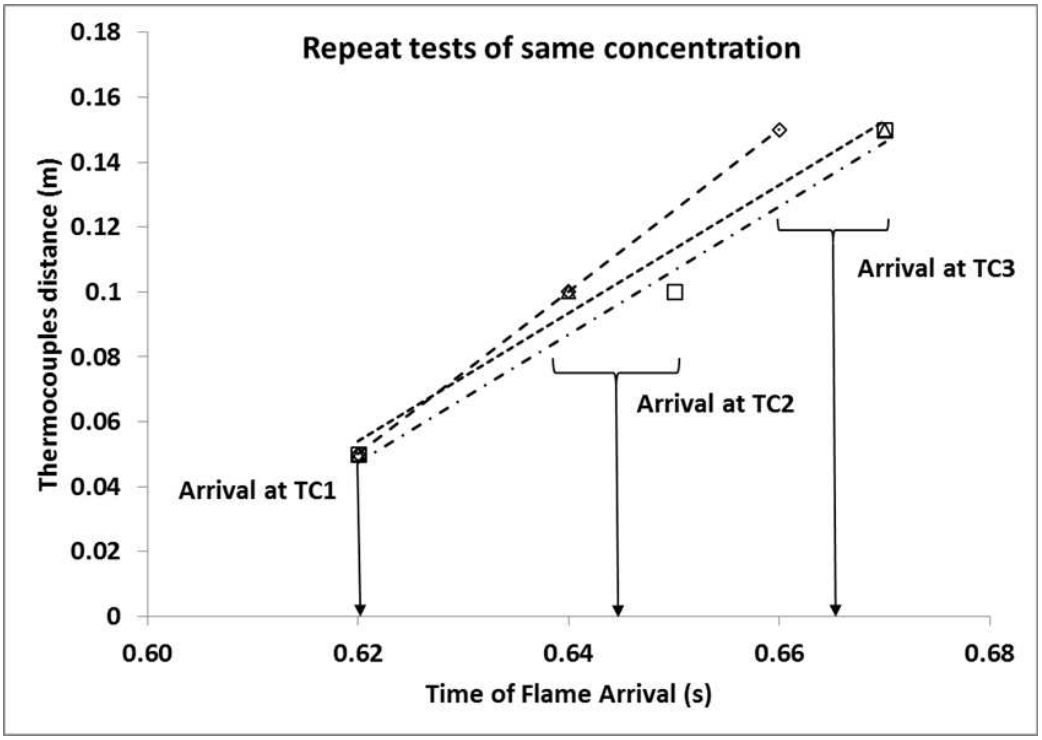


Figure 3: Example of flame speed measurement

3. Elemental and Proximate analysis

Elemental and proximate TGA (Thermogravimetric Analysis) results are shown in table 1 for the selected pulverized wood pellet samples. The %age carbon content was determined to be higher for wood pellet C sample with higher ash content and therefore is least reactive compared to the other pulverized wood samples. Pellet A and Pellet D samples showed higher proportions of oxygen compared to other wood pellet samples. Pellet D sample showed the higher volatiles yield and lowest fixed carbon content compared to other wood pellet samples. The calorific values were higher for wood samples carrying higher %age of carbon that is the principal elemental component and vice versa. Stoichiometric air to fuel (A/F) was also higher for wood samples with higher %age carbon contents for their complete conversion.

Table 1: Chemical characterization of the selected wood pellet samples

	Pellet A	**Pellet B**	**Pellet C**	**Pellet D**
%C (daf)	50.8	52.7	56.5	50.8
%H (daf)	5.9	6.1	6.0	4.7
%O (daf)	42.9	40.7	36.8	43.9
%N (daf)	0.4	0.5	0.6	0.4
%S (daf)	0.0	0.0	0.0	0.2
% Volatile matter (daf)	85.6	84.5	89.9	94.1

% Fixed carbon (daf)	14.4	15.4	10.1	5.9
% Moisture content	6.0	6.7	4.9	6.7
% Ash content	2.4	4.3	13	2.4
Calorific value (MJ/Kg) (daf)	21.2	21.6	22.3	21.0
Stoich. A/F (g/g) (daf)	6.0	6.4	7.0	5.6
Actual stoich. A/F (g/g)	5.5	5.7	5.7	5.1

4. Lessons Learned

4.1 Rate of pressure rise as a function of equivalence ratio ‘Ø’

The reactivity in terms of the maximum rate of pressure rise before the vent bursts for each wood samples is shown in Fig. 4 as a function of the equivalence ratio. Each test with fixed concentration was repeated three times and a best fit curve is plotted of maximum rate of pressure rise against equivalence ratio. The variation of maximum rate of pressure rise was ±20 bar/s that was due to uneven dust dispersion. The flame speeds were measured after the vent bursting in the Hartmann dust explosion tube. Maximum rate of pressure rise is the most appropriate reactivity parameter as it gives the average mass burning rate as showed in the experimental results. A critical feature of burner operation and of safety assessment is to know the worst case most reactive mixture, as explosion protection measures requires 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.

For pellet C sample as shown in Fig.4, the lean limit and most reactive concentration of the leaner size fraction (<63µm) were determined to be 0.67 and 1.33 in terms of equivalence ratio respectively. For the coarser size fraction (63-500µm), the lean limit was determined to be 0.85 and the most reactive concentration was observed to be even higher than 3.54 in terms of equivalence ratio. For the fraction of size (<500µm) containing mixture of fine and coarse particles, the lean limit and most reactive concentration were determined to be 0.78 and 1.77 respectively.

Similarly for pellet D sample, the lean limits of the size fractions <63, 63-500, <500µm were determined to be 0.38, 0.75 and 0.69 respectively. The most reactive concentrations for size fractions <63 and <500µm were determined to be same (1.56 in terms of equivalence ratio) and for size fraction 63-500µm, the most reactive concentration was found to be even higher than 3.13. For pellet A and pellet B milled samples, the lean limits for the size fractions <63, 63-500, <500µm were determined to be 0.36, 0.80, 0.51 and 0.46, 0.72, 0.65 in terms of equivalence ratio respectively. The most reactive concentration for milled pellet B sample was found to be 1.42 for <63 and <500µ size fractions and even higher than 3.80 for 63-500 size fraction. For milled pellet A sample, the most reactive concentration was found to be 1.82 for <63µm size fraction and higher than 3.64 for 63-500 and <500µm size range fractions.

From these results, it was summarized (MEC comparison in table 2 based on 0% ignition probability and last ignited concentration) that the finer sized fractions have the lower lean limit than the coarser fractions. The fractions comprising of fine and coarse particles (<500µm) were leaner than 63-500µm fraction that shows the strong influence of fine particles in the sensitivity of ignition. The most reactive concentration was observed to move from leaner to richer concentration with the increase in the size of the particles. It was concluded that careful consideration should be taken in the handling of these boiler feed-stocks and generation of fine particles due to wearing and tearing in the handling of wood pellets can cause the explosibility threats to the working environment.

Table 2: Comparison of the MEC of the selected pulverized wood pellet samples with good resolution for ignited and non-ignited concentrations

Materials	**MEC based on 0% ignition probability for extra safety Equivalence ratio, Ø**			**MEC based on last ignited conc. Equivalence ratio, Ø**		
	<63µm	<500µm	63-500 µm	<63µm	<500µm	63-500 µm
Pellet A	0.36	0.51	0.80	0.40	0.55	0.84
Pellet B	0.46	0.65	0.72	0.47	0.68	0.76

Pellet C	0.67	0.78	0.85	0.71	0.81	0.88
Pellet D	0.38	0.69	0.75	0.39	0.72	0.78

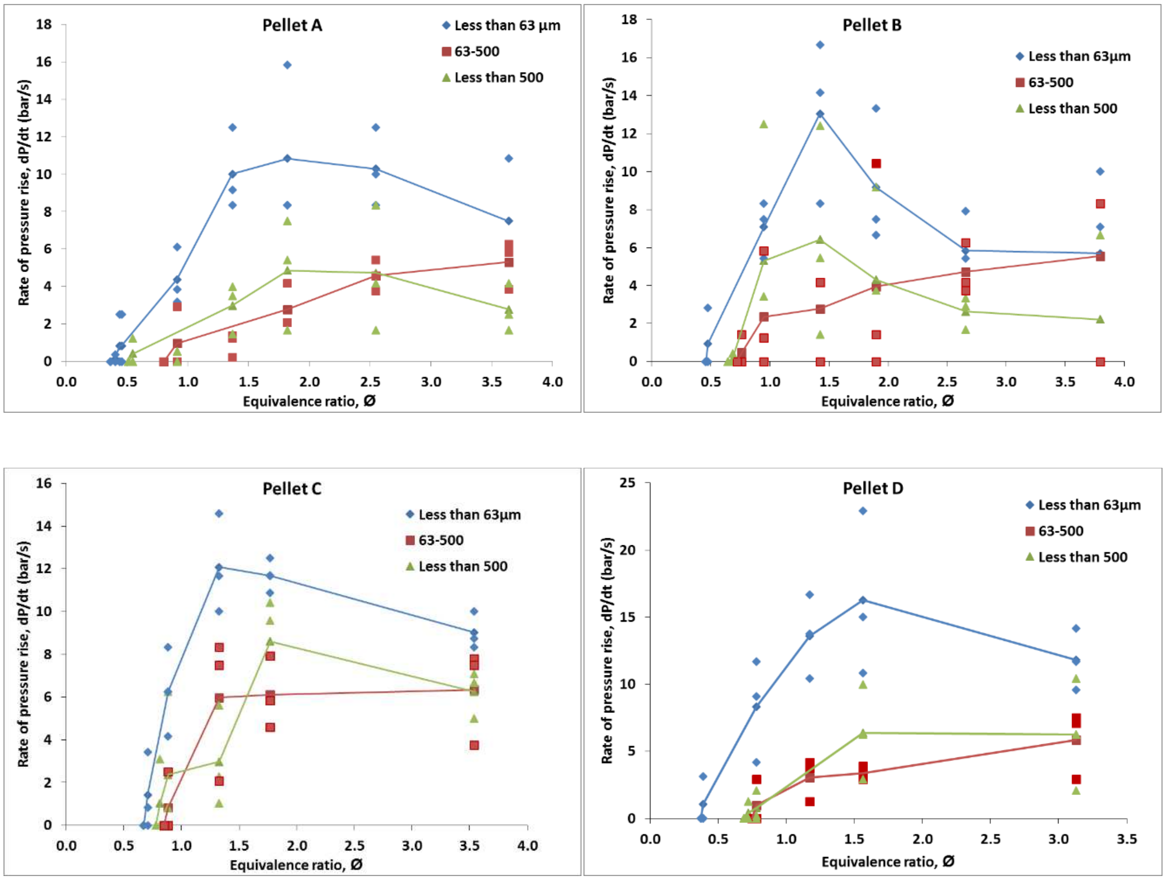


Figure 4: Rate of Pressure rise vs. equivalence ratio of varying size fractions of pulverised woody biomass

4.2 MEC as a function of particle size and ash+moisture contents

There is also strong influence of inert on the sensitivity and severity of explosion as pellet D sample showed leaner concentration than pellet C due to the presence of less inert ash. Two strong factors particles size and ash+moisture were plotted against MEC in terms of equivalence ratio as shown in Fig. 5 and Fig. 6 respectively. The mean particle size is taken from the different size range fractions and it was found that the MEC increases linearly with size till 250µm. For higher average size greater than 250µm, a sharp increase in the MEC was observed for all the wood pellets samples.

Wood samples showed different correlation than that of second generation crop residue samples. This is because of the higher size (d_{10}, d_{50} & d_{90}) of the wood samples as compared to residue samples measured by Malvern mastersizer 2000 as shown in table 3. Wood samples and residue samples showed good linear correlations of MEC with %ash+moisture contents separately as shown in Fig. 6.

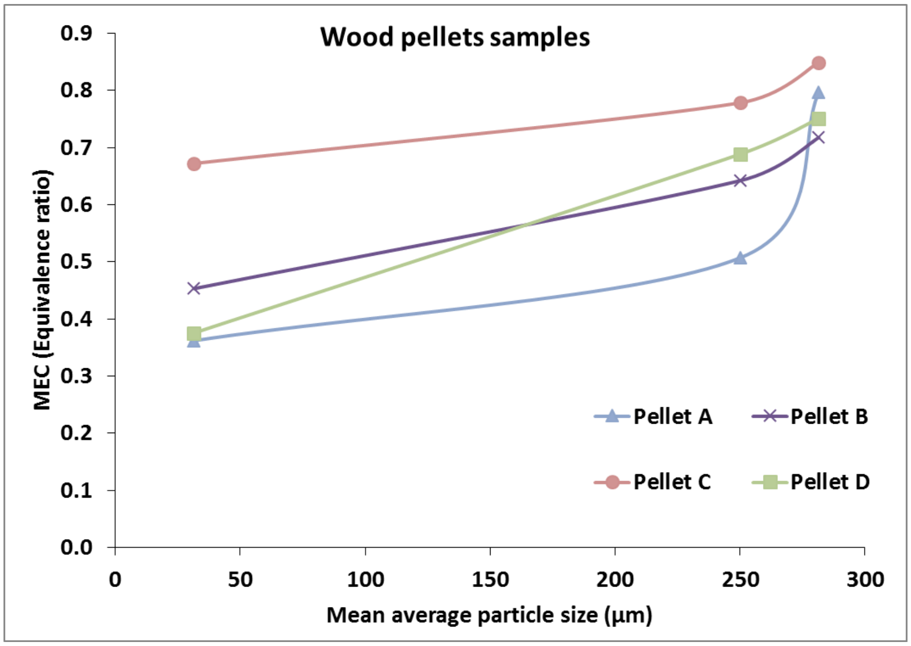


Figure 5: Comparison of the MEC vs. mean sieved particle size

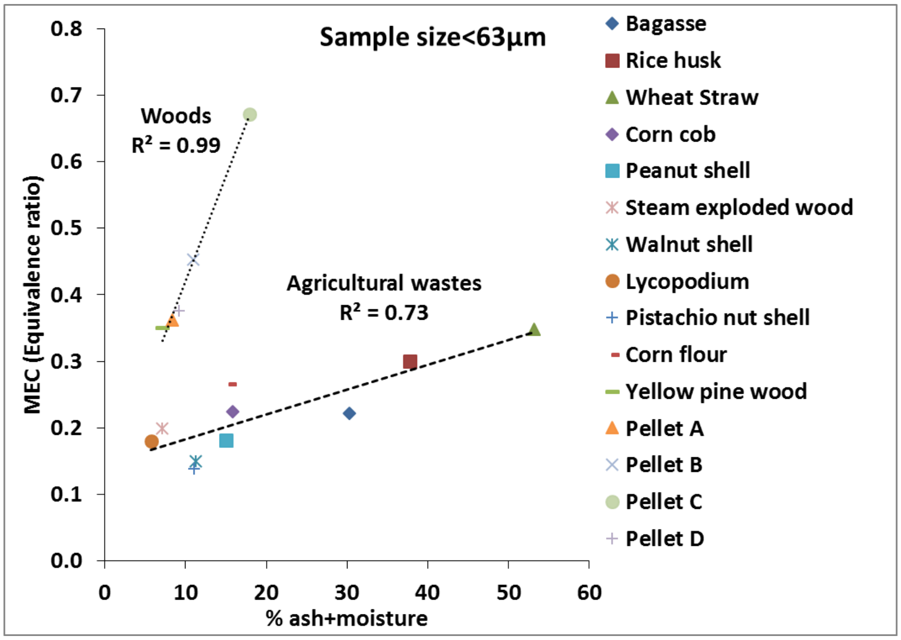


Figure 6: Correlation of MEC vs. ash+moisture content of agricultural wastes and woody biomass samples (Saeed et al., 2015, Saeed et al., 2016c, Saeed et al., 2016b, Sattar et al., 2012)

Table 3: Particle size distribution of the selected samples in comparison with other crop residue samples sieved to <63µm

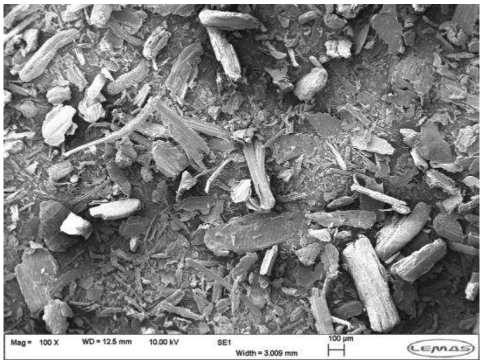
Materials	**Particle Size Distribution, µm**		
	d(10%)	**d(50%)**	**d(90%)**
Bagasse (B)	24.3	125.6	356
Wheat straw (WS)	18.78	126.1	441.5
Black pellets (BP)	13.3	51.9	151.8
Yellow pine wood (YPW)	30.68	198.3	629.6

Pellet A	28.03	184.16	576.28
Pellet B	33.02	180.38	569.24
Pellet C	37.09	194.62	608.8
Pellet D	34.46	223.06	636.12

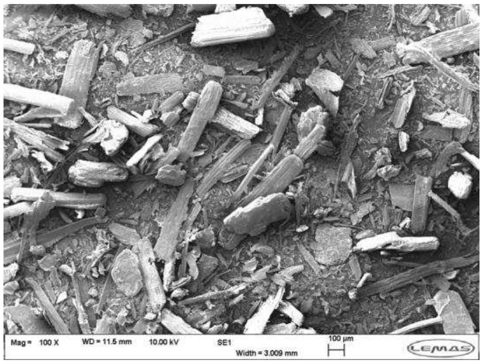
4.3 Scanning Electron Microscopy

Surface morphology study was also performed for wood and residue samples as shown in Fig. 7. It was observed crop residues samples like bagasse and wheat straw contain more fine fractions than the wood samples/ have particles shorter in length than wood samples. Also the crop residue's particles are relatively thin with fragile structure in comparison to wood samples that have rigid particles.

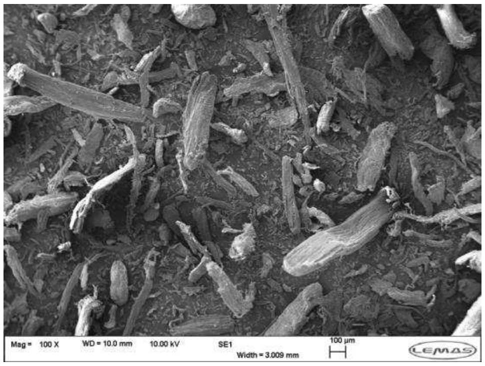
Bagasse



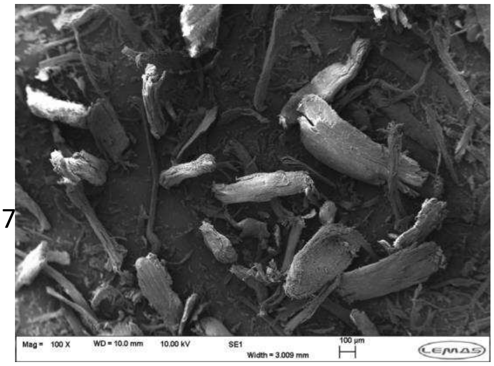
Wheat straw

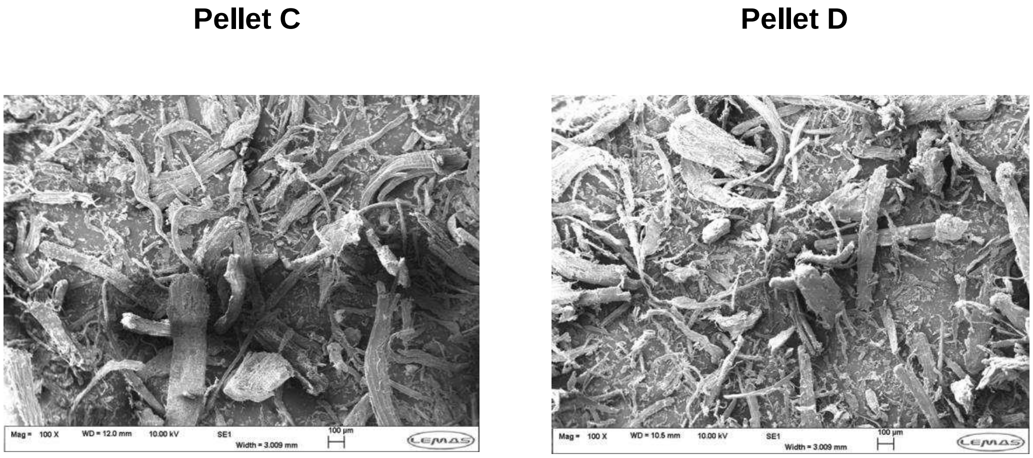


Pellet A



Pellet B





Pellet C **Pellet D**

Figure 7: Scanning Electron Microscopy of the residue samples in comparison to the wood samples

5. Conclusion

The modified Hartmann tube can be used to accurately determine the MEC and the concentration that has the highest reactivity. It can be used to determine the relative reactivity of different biomass dusts. Agricultural waste biomass dusts have high ash and moisture contents whereas the wood dusts have relatively coarse elongated particles size fractions for the same sieve size. These parameters act as inert heat sink and reduce the mixture reactivity and increase the MEC.

The ignition sensitivity and severity of the biomass wood dusts were found to be strongly dependent on particle size and the sum of ash and moisture contents. The

MEC correlates well with the mass fraction of the sum of ash and moisture contents for residues and wood dusts separately due to the difference in the particle size distribution. Reduction in the particle size and lower fraction of ash and moisture contents enhance the mixture explosiblity characteristics. Wood dust samples contain less ash contents as compared to residue samples but relatively coarse elongated particles act to increase the MEC. Mixture of fine and coarse particle size fractions (<500µm) have higher reactivity than the coarse size fraction (63-500µm) but lower reactivity than the fine fraction (<63µm) that shows the main role of fine particles in facilitating the ignition.

6. Acknowledgments

The authors would like to acknowledge the financial support to MAS provided by the University of Engineering and Technology, Lahore, Pakistan, in terms of ‘Faculty Development Program’. The authors are grateful to the EPSRC Energy Programme (Grant EP/H048839/1) for financial support of part of this work.

References

BADGER, P. C. & FRANSHAM, P. 2006. Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs—A preliminary assessment. Biomass and bioenergy, 30**,** 321-325.

BOMAN, C., NORDIN, A. & THANING, L. 2003. Effects of increased biomass pellet combustion on ambient air quality in residential areas—a parametric dispersion modeling study. Biomass and Bioenergy, 24**,** 465-474.

CASHDOLLAR, K. L. 1996. Coal dust explosibility. Journal of loss prevention in the process industries, 9**,** 65-76.

CASHDOLLAR, K. L. 2000. Overview of dust explosibility characteristics. Journal of Loss Prevention in the Process Industries, 13**,** 183-199.

DEMIRBAŞ, A. 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. Energy Conversion and Management, 42**,** 1357-1378.

ECKHOFF, R. K. 2003. Dust Explosions in the Process Industries: Identification, Assessment and Control of Dust Hazards, Amsterdam, Gulf Professional Publishing.

HERTZBERG, M. & CASHDOLLAR, K. L. 1987. Introduction to dust explosions.

HERTZBERG, M., CASHDOLLAR, K. L., NG, D. L. & CONTI, R. S. 1982. Domains of flammability and thermal ignitability for pulverized coals and other dusts: particle size dependences and microscopic residue analyses. Symposium (International) on Combustion, 1982. Elsevier, 1169-1180.

HUÉSCAR MEDINA, C., PHYLAKTOU, H. N., SATTAR, H., ANDREWS, G. E. & GIBBS, B. M. 2013. The development of an experimental method for the determination of the minimum explosible concentration of biomass powders. Biomass and Bioenergy, 53**,** 95-104.

HUÉSCAR MEDINA, C., SATTAR, H., PHYLAKTOU, H. N., ANDREWS, G. E. & GIBBS, B. M. Explosibility of biomass and torrefied biomass powders: Determination of Minimum Explosible Concentrations. Proc. 20th European Biomass Conference and Exhibition, 2012 Milan.

KUMAR, A., CAMERON, J. B. & FLYNN, P. C. 2003. Biomass power cost and optimum plant size in western Canada. Biomass and Bioenergy, 24**,** 445-464.

PALMER, K. N. 1973. Dust explosions and fires, Chapman and Hall London;.

PILÃO, R., RAMALHO, E. & PINHO, C. 2006. Overall characterization of cork dust explosion. Journal of hazardous materials, 133**,** 183-195.

SAEED, M. A., ANDREWS, G. E., PHYLAKTOU, H. N. & GIBBS, B. M. 2016a. Global kinetics of the rate of volatile release from biomasses in comparison to coal. Fuel, 181**,** 347-357.

SAEED, M. A., ANDREWS, G. E., PHYLAKTOU, H. N. & GIBBS, B. M. 2016b. Raw and steam exploded pine wood: Possible enhanced reactivity with gasification hydrogen. International Journal of Hydrogen Energy.

SAEED, M. A., ANEZ, N. F., ANDREWS, G. E., PHYLAKTOU, H. N. & GIBBS, B. M. 2017. Steam exploded pine wood burning properties with particle size dependence. Fuel, 194**,** 527-532.

SAEED, M. A., MEDINA, C. H., ANDREWS, G. E., PHYLAKTOU, H. N., SLATTER, D. & GIBBS, B. M. 2015. 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. Flame speed and Kst reactivity data for pulverised corn cobs and peanut shells Proceedings of the 11th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosion (ISHPMIE), 24-29 July 2016c Dalian, China.

SATTAR, H., PHYLAKTOU, H. N., ANDREWS, G. E. & GIBBS, B. M. 2012. Explosions and Flame Propagation in Nut-shell Biomass Powders. Proc. of the IX International Seminar on Hazardous Process Materials and Industrial Explosions (IX ISHPMIE), 2012 Cracow.

SCHOBERT, H. H. 2013. Chemistry of Fossil Fuels and Biofuels, United States of America, Cambridge University Press, New York.

SLATTER., D. J. F., HUÉSCAR MEDINA, C., SATTAR, H., ANDREWS, G. E., PHYLAKTOU, H. N. & GIBBS, B. M. 2013. The Influence of Particle Size and Volatile Content on the Reactivity of CH and CHO Chemical and Biomass Dusts. Proc. of the 7th International Seminar on Fire and Explosion Hazards, 2013 Providence, RI, USA.

TILLMAN, D. A. 2000. Biomass cofiring: the technology, the experience, the combustion consequences. Biomass and Bioenergy, 19**,** 365-384.

VASSILEV, S. V., BAXTER, D., ANDERSEN, L. K. & VASSILEVA, C. G. 2010. An overview of the chemical composition of biomass. Fuel, 89**,** 913-933.

WILÉN, C., MOILANEN, A., RAUTALIN, A., TORRENT, J., CONDE, E., LODEL, R., CARSON, D., TIMMERS, P. & BREHM, K. 1999. Safe handling of renewable fuels and fuel mixtures, Technical Research Centre of Finland.

WILSON, T. O., MCNEAL, F. M., SPATARI, S., G. ABLER, D. & ADLER, P. R. 2011. Densified biomass can cost-effectively mitigate greenhouse gas emissions and address energy security in thermal applications. Environmental science & technology, 46**,** 1270-1277.

ZANZI, R., SJÖSTRÖM, K. & BJÖRNBOM, E. 2002. Rapid pyrolysis of agricultural residues at high temperature. Biomass and Bioenergy, 23**,** 357-366.