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Steam Exploded Pine Wood: The Influence of Particle Size on Mixture Reactivity

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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 measurements of the minimum explosion concentration (MEC), flame speed, K_{st} , and peak pressure for pulverised pine wood and steam exploded (black pellets) pine wood. The ISO 1 m^3 dust explosion vessel was used, modified to operate on relatively coarse paticles, using a hemispherical dust disperser on the floor of the vessel and an external blast of 20bar compressed air. The pulverized material was sieved into the size fractions <500µm, <63, 63-15-, 150-300, 300-500µm to study the coarse particles used in biomass power generation. The MEC was measured in the range of 0.6-0.85 burnt equivalence ratio, $Ø_{burnt}$,. The measured K_{st} (25-60 bar m/s) and turbulent flame speeds (~1.5 - 5 m/s) These results show that the steam exploded pine biomass was more reactive than the raw pine, due to the finer particle size for the steam explosed biomass.

Keywords: Steam Exploded Biomass, Explosibility, Flame propagation.

1. Introduction

Pulverised wood or pulverised agricultural waste biomass are effective substitutes for pulverised coal as low CO_2 fuels and hence can be used to reduce GHG emissions from coal fired power generation [1, 2]. In the UK pulverized woody biomass burning in existing coal fired power stations generated 5.7% of electricity in 2014 [3]. However, these raw biofuels have low bulk densities and low calorific values, making their handling and transportation a challenge. They are normally converted into compressed dried pellets at the biomass source and these increase the bulk density and reduce dust in transport. The lower water content compared with the raw biomass increases the calorific value, CV, which reduces the transport costs per GJ of energy transported.

Adoption of further thermal pre-treatment such as torrefaction [4, 5] or steam exploded biomass [6, 7], further increases the bulk density and the CV and further reduces the water content. Torrefied biomass involves heating at around 260 – 320^{o}C, then pulverisation and compression into pellets. Steam exploded biomass involves heating to similar temperatures as for torrefaction, with hot steam at high pressure and then releasing this pressure so that the water absorbed in the biomass ‘explodes’ out, shattering the biomass. These thermal pretreatment processes of the raw biomass also makes the subsequent pellets stronger with less associated dust and less water absorption.. The net result is a further reduction in the transport costs per GJ of energy, which will more than pay for the increased processing costs of the biomass. When delivered to the power station the thermally treated biomass can be milled alongside coal as the thermal treatment process makes the particles brittle. The thermal treatment creates a physical change in the structure of the fibrous biomass that makes the fibres brittle. This makes the thermally treated biomass more like coal and sometimes it is referred to as ‘biocoal’; although a precise definition of this term is lacking at present.

Thermally treated biomass using the steam exploded biomass process is investigated in the present work, using samples provided from an industrial scale pilot plant [6, 7] for this process. The authors [6] have previously investigated steam exploded biomass using the Hartmann dust explosion equipment [8] and reported MEC data and flame speeds and compared them with the raw biomass. This work showed that steam exploded biomass was more reactive than the raw biomass, but this was mainly due to the particle size differences [6]. The steam exploded biomass had finer particles due to their brittle fibres breaking up more easily [5] during the steam explosion process. In the present work the same steam exploded biomass was investigated using the ISO 1 m^3 dust explosion equipment [9]. The emphasis is on the measurement of the reactivity of the same steam exploded and raw pine pulverized biomass by measuring the spherical turbulent flame speed and deriving the laminar flame speed and burning velocity. The peak pressure and the deflagration index, $K_{st} = dp/dt_{max} V^{1/3}$, were also determined.

The physics of flame propagation in pulverized biomass/coal burners is identical to that which occurs in spherical flame propagating pulverised biomass flames in explosions, so that the present work is not just about explosion hazards but also about flame propagation in pulverized fuel burners [9]. Biofuels carry fire/explosibility risks in their handling [10, 11] and there is little published information on this as the standard 1 m^3 explosion vessel with ‘C’ ring dust disperser does not work with fibrous biomass [9], which is why there was little data on biomass dusts. Lots of biomass fire/explosion incidents were reported in past [11] and it is of concern that there is a lack of reliable explosion protection for biomass dusts, which makes the design of protection equipment uncertain [9, 10]. The reliable measurements of the reactivity parameters for these biofuels depend on multiple factors such as fuel properties and their size distribution [12].

Low temperature (~300^{o}C) thermal pre-treatment of biomass results in small chemical changes in their compositions but greater physical changes in the break up of the structure of the fibres [10, 12]. These thermally treated fuel pellets mill in a similar way to coal and can more easily used to replace coal for the existing facilities than raw wood pellets. However, there is little known about the combustion characteristics of these thermally treated biofuels. It was found that coals become non-reactive for very coarse size due to their rigid thick structure delaying the efficient release of volatiles [13], whereas the biomass particles are porous with thin cell walls.

Slatter et al. [14] and Saeed et al. [2] showed that pine wood and bagasse samples respectively with particle size 300-500 μm would propagate a flame and Dong et al. [15] found that wood dust sizes up to 1200μm could explode if they were dry. All these investigators found that biomass had a leaner MEC and higher values of K_{st} for finer particles, but that the peak overpressure was high for all sizes. Cashdollar et al. [16] have shown that the reactivity of coal dust decreases with increase in particle size, but 150μm was the largest size that they reported exploded. Gao et al. [17] have shown a similar dependence of mixture reactivity on particle size for high MW flammable liquids, but not to the side range that dusts were found to be flammable [2, 14, 15]. In this work the explosion characteristics and spherical turbulent flame speed of steam exploded pine wood were determined as a function of the particle size.

2. Experiments

2.1 Experimental materials

Pine wood with the ‘steam explosion’ thermal treatement was supplied by Zilkha Biomass Energy in the form of pellets. Around 20 kg of pellets were milled using Retch 100 ultrafine grinder to less than 500 μm and sieved for the following size fractions <63 μm, 63-150 μm, 150-300 μm and 300-500 μm. There was insufficient raw biomass supplied to undertake tests in the ISO 1 m^3 vessel, but the comparison with the raw pine wood and the steam exploded pine wood has been carried out using the Hartmann explosions equipment by Saeed et al. [6]. This showed that steam exploded pine wood was more reactive than raw pine wood in terms of a leaner MEC and higher flame speeds and initial rates of pressure rise in the Hartmann. However, this higher reactivity was due to the finer particle size for steam exploded biomass.

2.2 Chemical Characterization of the raw pine wood in comparison to its steam exploded pine

The steam exploded pine wood was analysed for its elemental and TGA proximate characterizations. Elemental analysis was performed using Flash 2000 thermoscientific analyser and TGA analysis was performed using Shimadzu TA 50 after selecting a suitable temperature program as had been explained in several other previous works [15]. Table 1 showed the chemical characterization of raw pine wood in comparison to steam exploded pine. Elemental compositions were found to be almost same for raw and steam exploded wood however, a small increase in fixed carbon and proportional reduction in volatiles were measured in the steam exploded wood due to steam explosion treatment. Steam exploded wood also found to have higher true density with less porosity as compared to raw pine wood sample.

Also particle size distributions of raw and steam exploded pine wood with different sieved sizes were presented in fig. 1. It was found that the fineness of raw pine wood was increased after steam explosion treatment. This increase in fineness of the steam exploded pine wood was due to shattering of structure and increase in the brittleness of the particles. Also the increase in size fraction of this steam exploded pine wood approached to the same particle size distribution as that of raw pine wood.

Table 1: Chemical Characterisation of raw pine wood in comparison to its steam exploded sample

Chemical characterisation	**Raw pine wood (YPW)**	**Steam exploded pine wood (BP)**
% C (daf.)	51.0	52.8
% H (daf.)	6.1	5.8
% N (daf.)	0.0	0.4
% S (daf.)	0.0	0.0
% O (daf.)	42.9	41.1
% H2O	5.4	4.4
% VM	77.5	73.0
% VM (daf.)	83.4	78.6
% FC	15.3	19.9
% Ash	1.7	2.7
CV (MJ/Kg)	19.9	19.5
CV (MJ/Kg) daf.	21.4	21.0
Stoich. A/F (g/g)	6.1	6.3
Actual stoich. conc. (g/m^3)	211.2	205
Bulk density (kg/m^3)	629.0	436.7
True/particle density (kg/m^3)	1678	1751.5

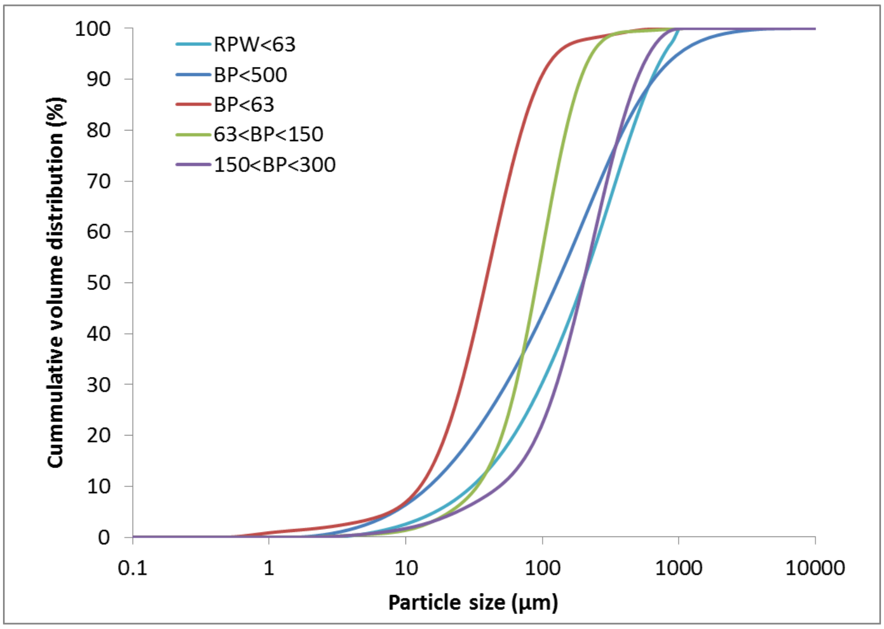


Fig. 1: Cumulative analysis of raw pine in comparison to its steam exploded sample of different sized fractions

2.3 Experimental Methodology

Modified ISO 1 m^3 vessel as shown in fig. 2 was used for the measurement of explosibility indices of different sized fractions of steam exploded pine wood. This vessel has a design pressure of 25 bar,g to withstand and designed based on ISO 6184/1 (1985) standard. Details of this modified vessel and experimental methodology had been explained in several other works [16-19]. Repeatability of the tests were checked periodically for different sample and were found to be within allowable limits [20]. Different explosibility characteristics like turbulent and laminar flame speed, pressure rise due to burning and peak rate of pressure rise after some degree of smoothing were measured and plotted against burnt equivalence ratio. Burnt equivalence ratio was calculated after accounting the unburnt mass left in the vessel plus the inclusion of ash contents due to burnt mass proportion in the propagation of flame. This actual burnt concentration was the true representative concentration with an error of ± 5% for its estimation.

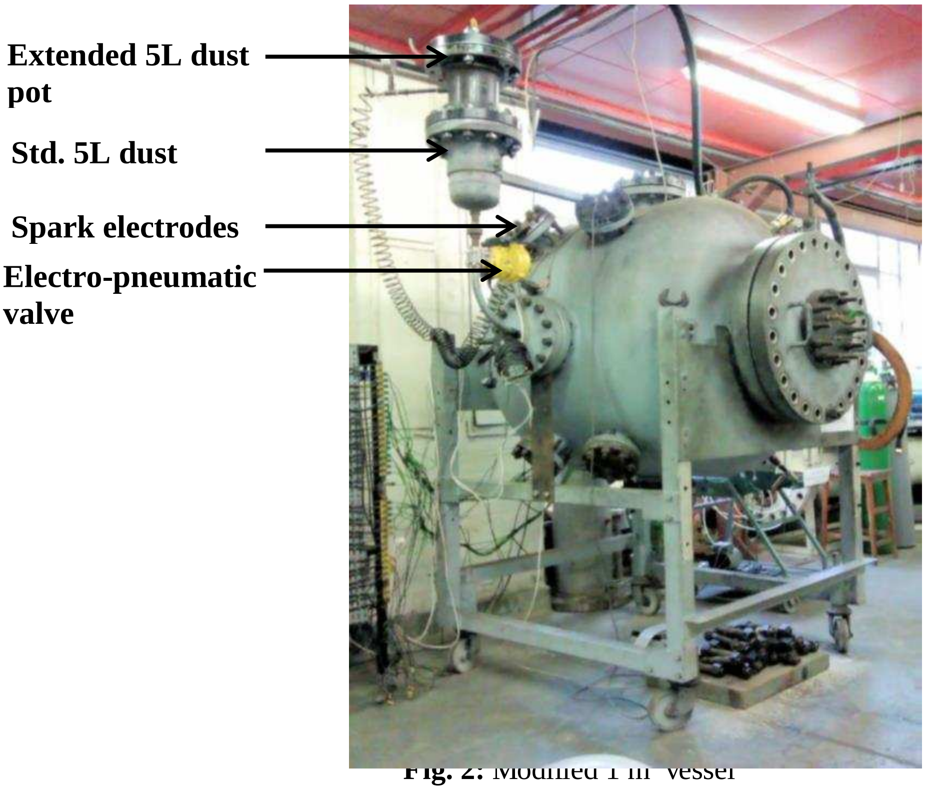


Fig. 2: Modified 1 m^3 vessel

Calibrated hemispherical disperser with drilled pipe as shown in fig. 3 was calibrated for testing of coarse and fibrous samples having dispersing issues using standard C ring disperser. Drilled pipe had an inside diameter of 20 mm with 3mm wall thickness. There were total 9 holes in the drilled pipe of 6 mm inside diameter to have almost same flow area (254 mm^2) as in the standard C ring disperser (263 mm^2). Diameter of the hemispherical cup was selected as 358 mm to accommodate enough amount of high voluminous biomass dust. Calibration was performed using standard corn flour and Colombian coal samples. Explosibility results and residue mass left showed good comparison with % error of around less than 5% for the most reactive concentrations. Also the turbulence factor for this calibrated disperser was measured using turbulent to laminar flame speeds/ turbulent to laminar deflagration indices ratio for 10% Methane. Measured turbulence factor of 4.7 was almost same and within the range of turbulence factors measured for standard C ring disperser [21-23].

Fig. 3: Calibrated hemispherical disperser

3. Results and discussion

3.1 Reactivity of steam exploded samples of different sized fractions

Reactivity of different size ranged steam exploded fractions were measured in terms of rate of pressure rise, flame speed and maximum rise of pressure due to burning relative to ambient pressure. Complete concentration profile could not be obtained due to limited amounts of sized fractions.

3.1.1 Deflagration index vs. burnt equivalence ratio

Fig. 4 showed the deflagration index (K_{st}) of different size ranged fractions of steam exploded pine wood against burnt equivalence ratio. It was found that fine particles had fast rate of propagation of flame with higher deflagration index compared to coarse sized fraction. Also it was found that the least reactive concentration was leaner than the coarse fractions. The coarse fraction with higher average particle size (300-500 μm) did not explode even for 1500 g/m^3 nominal concentration. Based on the trends of the coarse fraction, it can be assumed that coarse fraction required very rich concentration for their most reactive concentration.

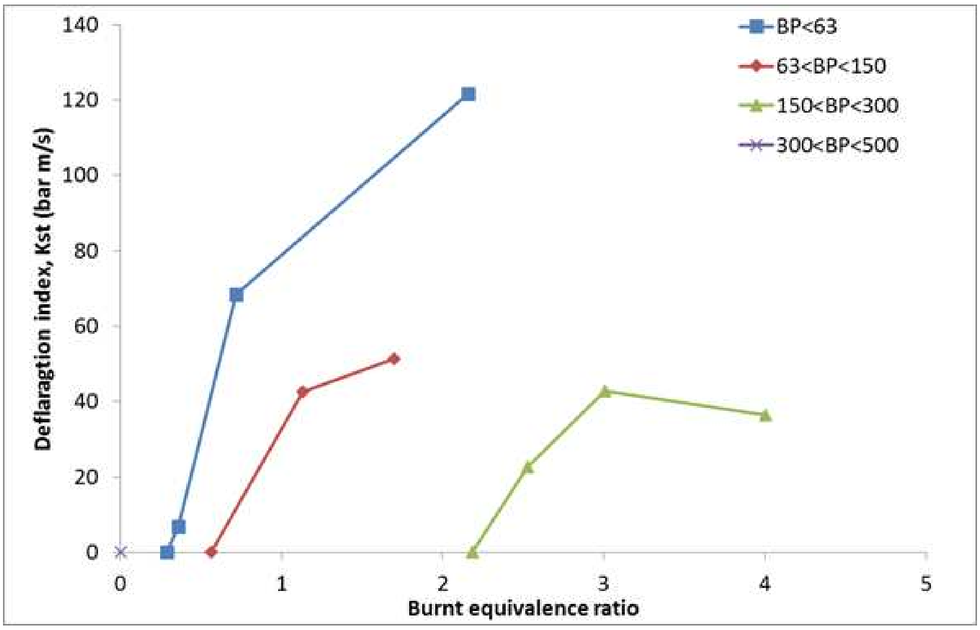


Fig. 4: K_{st} vs. burnt equivalence ratio for different sized fractions steam exploded pine wood (BP)

Flame development and propagation was mainly due to release of volatiles that was with some delay due to thicker particle surface of the coarse particles. This enough release of volatiles for sustained development of flame needed higher amount of dust in the available time for the volatile’s release. Fine particles had more exposed surface area and they released higher volatile’s yield efficiently resulting higher rate of pressure rise. Fig. 4 showed the peak deflagration indices for the tested concentrations of these limited fractions to be in the range of 43-122 bar m/s with the higher value for the fine fraction. Very coarse fraction of size range 300-500 µm failed to ignite due to limited release of volatiles with existing concentration.

3.1.2 Peak pressure relative to atmospheric pressure vs. burnt equivalence ratio

Ratio of maximum pressure due to instantaneous burning relative to ambient pressure were plotted against burnt equivalence ratio for different sized fractions of steam exploded pine wood as shown in fig. 5. It was noticed that fine fractions were burning more with higher rise of pressure as compared to coarse fraction (150-300 µm) that was levelling at lower peak pressure ratio of around 7 bar. Finer fraction (< 63 µm) showed peak pressure ratio of around 8.6 bar with further rise for higher concentration that could not be tested due to limited amount of dust. Similarly the size fraction having moderate size 63-150 µm giving the peak pressure ratio in between fine and coarse fractions. It meant that presence of fine facilitated the efficient propagation of flame with higher mass burning. Very coarse fraction of size 300-500 µm could not turn to enough gas for the flame propagation.

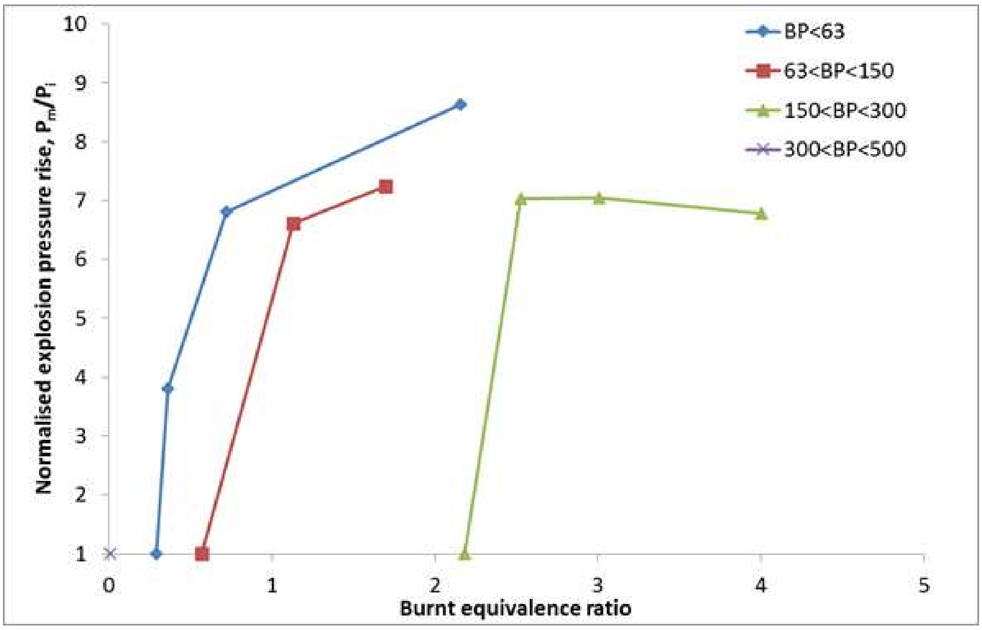


Fig. 5: P_m/P_i vs. burnt equivalence ratio for different sized fractions steam exploded pine wood (BP)

3.1.3 Turbulent flame speed vs. burnt equivalence ratio

Turbulent flame speed were also plotted for these different sized fractions against burnt equivalence ratio as shown in fig. 6. Flame speeds showed the same trend as deflagration index (K_{st}) for different burnt concentrations. Peaks flame speeds were measured to be in the range of 1.4-5.4 m/s with higher flame speed for the finer fraction. Greater proportion of fines resulted the quick release of volatiles with their maximum rate of combustion. Increasing the sieved size showed declined slope due to delay in the evolution of volatiles from the coarse particles for flame propagation. Also less mass burning of coarse fractions showed less flame speed until a very coarse sized fraction (300-500 µm) that could not support the propagation of flame.

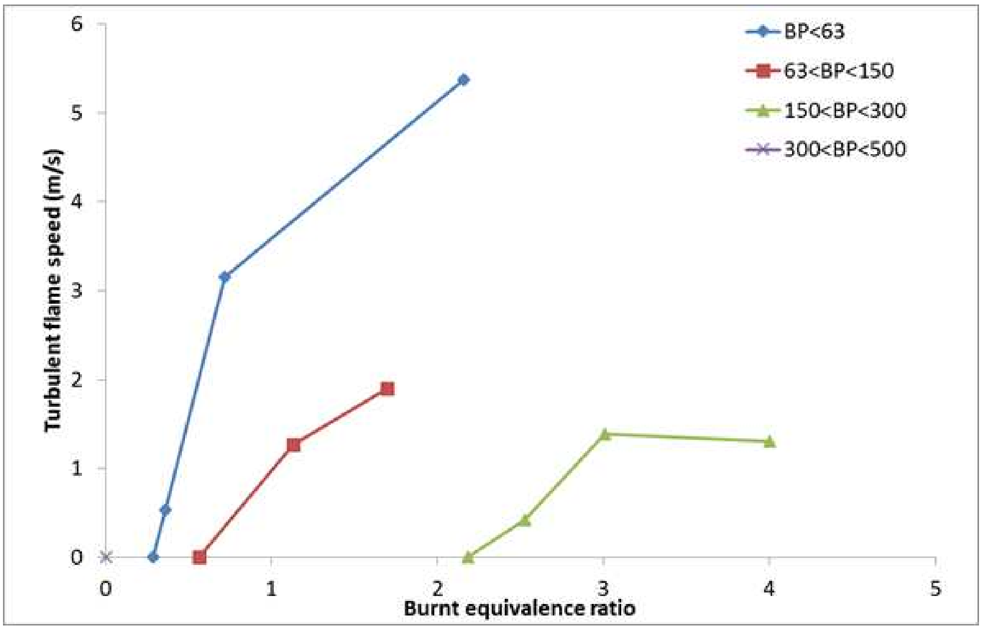


Fig. 6: Turbulent flame speed vs. burnt equivalence ratio for different sized fractions steam exploded pine wood (BP)

3.2 Analysis of rice husk post explosion residues

3.2.1 Ultimate and proximate analysis of post explosion residues

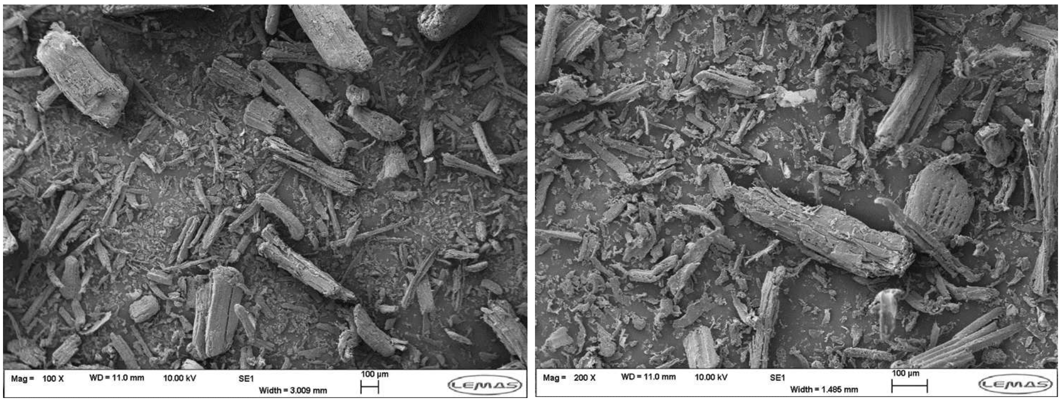
Post explosion residues of the most reactive concentration from different sized range fractions were analysed and compared with raw steam exploded pine wood as shown in table 2. It was found that the residue samples had almost same elemental and TGA analysis with only the significant difference of ash and volatile contents. This addition of ash in the residue was due to burnt mass proportion forming combustion products of carbon dioxide and water. Carbon dioxide and some of the water vapors were discharged in the purging process leaving ash behind enriching the unburnt mass left in the vessel. It was found that more ash was found in the post explosion residue of finer fraction due to more mass burning whereas comparatively less ash was measured in the coarser fraction indicating less burning of coarse particles. The reduction of volatiles was due to relative enhancement of ash proportion in the residue samples as the highest increase of ash in the finer fraction resulted the maximum reduction of volatiles.

Table 2: Chemical characterization of the post explosion residues of different sized fractions in comparison to raw steam exploded pine

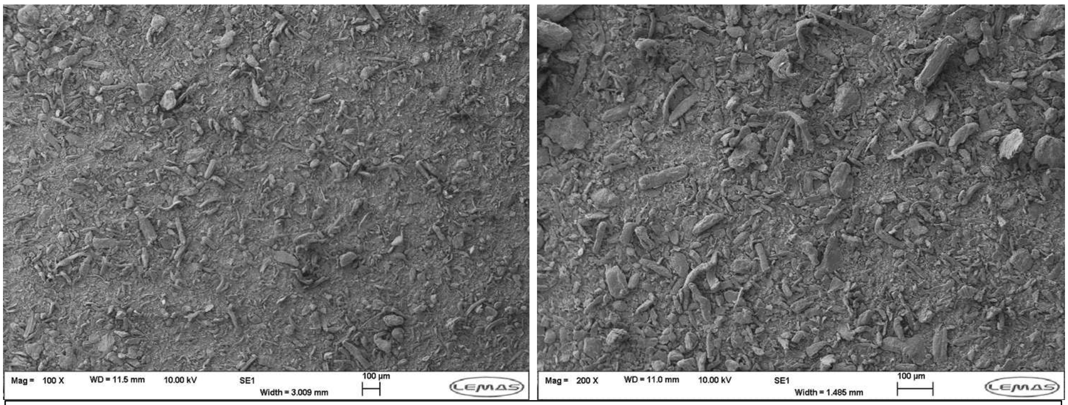
Biomass	**Steam exploded pine wood (BP)**	**Post explosion steam explosion residues**		
		BP<63µm	**BP(63-150µm)**	**BP<500µm**
% C (daf.)	52.8	55.4	53.6	53.0
% H (daf.)	5.8	6.0	6.0	6.1
% N (daf.)	0.4	0.5	0.4	0.4
% S (daf.)	0.0	0.0	0.0	0.0
% O (daf.)	41.1	38.1	40.0	40.5
% H2O (ar.)	4.4	4.8	4.7	5.8
% VM (ar.)	73.0	64.3	67.9	67.7
%VM (daf.)	78.6	73.9	76.9	76.8
% FC (ar.)	19.9	22.7	20.4	20.4
% Ash (ar.)	2.7	8.2	7.02	6.1
CV (MJ/kg)	19.5	19.6	19.3	19.3
Stoich. A/F (g/g)	6.3	6.8	6.5	6.4
Actual stoich. conc. (g/m^3)	205	202.8	209.1	212.8

3.2.2 Surface morphological study

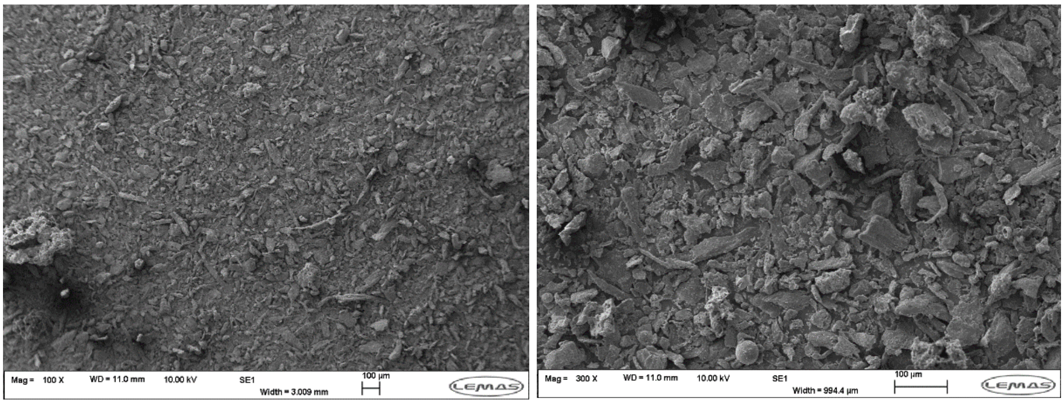
Scanning electron microscope imaging were also compared for the finer samples of the raw pine wood with its steam exploded and the post explosion residue sample as shown in fig. 7. It was found that there were enrichment of fines in the steam exploded pine wood that actively participated in the flame propagation. The residue sample showed fused and molten ash with some of the mass unburnt that was exactly same as that of the original material. Also the elemental and TGA analysis revealed the same unburnt mass as the original. For the coarse fraction, there were formation of holes observed on the surface indicating the role of volatiles in the flame propagation. However, the fine fractions contributed fully leaving inert behind for the most reactive concentration.



Raw pine wood sample<63µm



Steam exploded pine sample<63µm



Steam exploded pine post explosion residues<63µm

Fig. 7: Scanning Electron Microscopy of raw pine, steam exploded pine and post explosion residue of steam exploded pine wood

3.3 Comparison of modified ISO 1 m^3 and previous Hartmann results

MEC were close to each other based on Hartmann and 1 m^3 measurements. Also it was noticed that the rate of pressure rise in 1 m^3 vessel was of the order of 6 as compared to Hartmann measurements. There was quick quenching in the Hartmann due to small diameter tube giving less rate of pressure rise compared to 1 m^3 vessel. Also it reflected that the most reactive concentration was at an equivalence ratio of around 1.8 based on both experimental techniques for extrapolated prediction of $1m^3$ results.

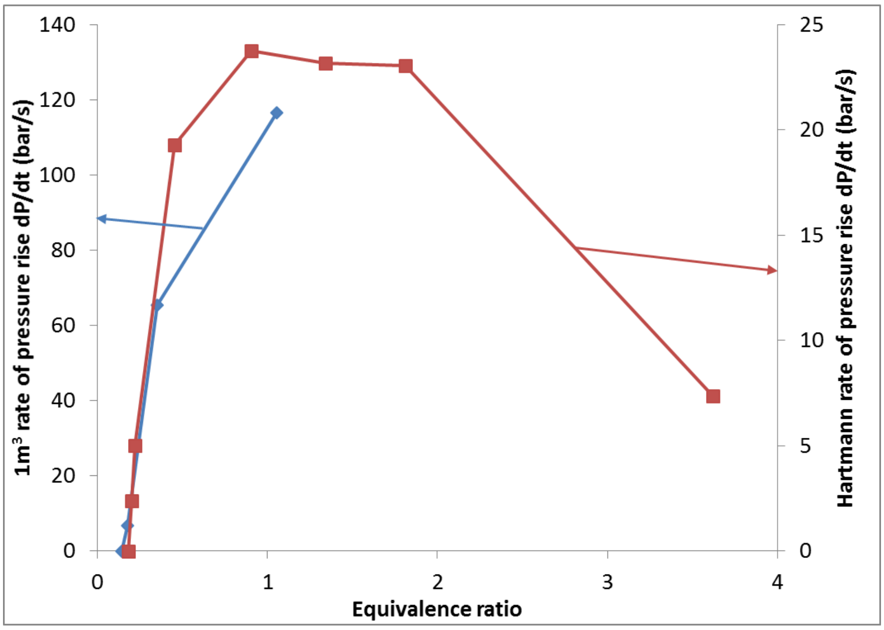


Fig. 8: Comparison of rate of pressure rise from 1 m^3 and Hartmann measurements against equivalence ratio for fine fraction of steam exploded wood< 63 μm [15]

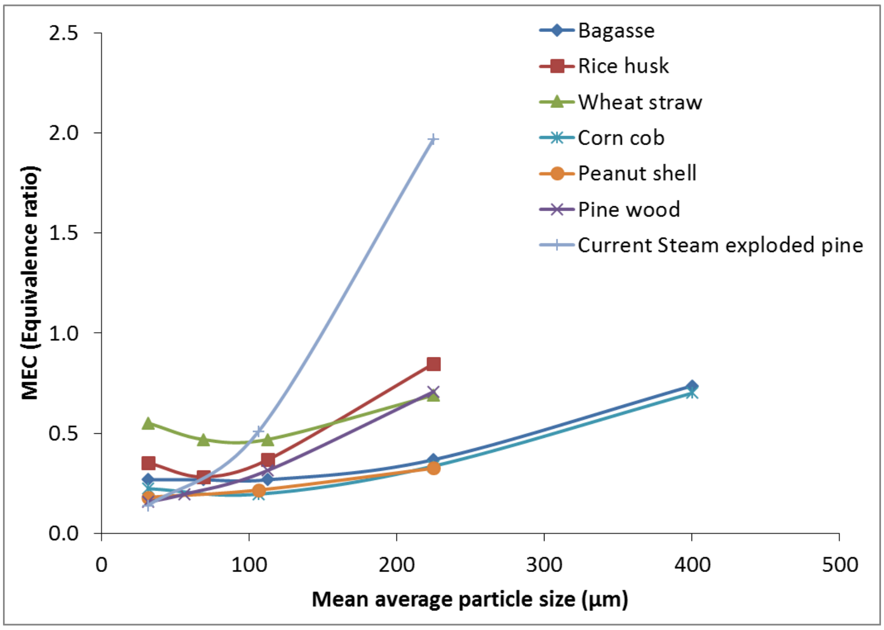


Fig. 9: Comparison of rate of pressure rise from 1 m^3 and Hartmann measurements against equivalence ratio for fine fraction of size < 63 μm [2]

Effect of average particle size on the minimum explosive concentration of the selected steam exploded pine wood was compared with raw biomass samples based on Hartmann measurements as shown in fig. 9. It was found that steam exploded pine wood showed the leaner concentration than the other raw biomass samples for the finer fraction of average particle of 31.5 µm. However with increasing particle size, the sensitivity of explosion reduced drastically than the raw biomass samples. Previous Hartmann results were based on pre-existing spark overestimating the lean limits and needs improvements in its methodology as explained in other work [24]. Detailed assessment of these renewable fuel based on explosibility characteristics were carried out before their employment for safe working environment

4. Conclusions

In this work, different size range fractions of steam exploded pine wood were tested to investigate the flame propagation behavior and effect of particle size. It was revealed that steam explosion treatment enhanced the proportions of fines compared to raw pine wood with more fibrous and elongated particles. Explosiblity results concluded that the finer fraction with more fines participated actively with more mass burning and higher flame speed. Increasing the size of the fraction reduced the intensity of combustion with less flame speed and deflagration indices. Very coarse fraction containing no fines failed to propagate the flame due to delay in the burning of these coarse particles. Also the post explosion residues showed the same analysis as that of original steam exploded pine wood with the addition of ash due to burnt particles affecting the relative proportions of volatiles reduction. This work confirmed the severity of reaction with reduction in sizes and vice versa that need to be accessed fully before their adoption as fuel for the power generation plants.

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