



## Full Length Article

# Steam exploded pine wood burning properties with particle size dependence



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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, deflagration index ( $K_{st}$ ), and peak pressure for pulverised pine wood and steam exploded pine wood (SEPW). The ISO 1 m<sup>3</sup> dust explosion vessel was used, modified to operate on relatively coarse particles, using a hemispherical dust disperser on the floor of the vessel and an external blast of 20 bar compressed air. The pulverized material was sieved into the size fractions <500  $\mu$ m, <63  $\mu$ m, 63–150  $\mu$ m, 150–300  $\mu$ m, 300–500  $\mu$ m to study the coarse particles used in biomass power generation. The MEC ( $\emptyset$ ) was measured to be leaner for finer size fraction with greater sensitivity of explosion. The measured peak  $K_{st}$  was 43–122 bar m/s and the maximum turbulent flame speeds  $\sim$ 1.4–5.4 m/s depending on the size distribution of the fraction. 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 exploded biomass.

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## 1. Introduction

Pulverised wood or pulverised agricultural waste biomass are effective substitutes for pulverised coal as low CO<sub>2</sub> 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 [4]. The lower water content compared with the raw biomass reduces the transport costs per GJ of energy transported.

Adoption of further thermal pre-treatment such as torrefaction [5,6] or steam exploded biomass [7,8], further increases the bulk density and reduces the water content. Torrefied biomass involves heating at around 200–320 °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 cost saving safe and cheap transportation compared to the thermal 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 for this process. The authors [7] have previously investigated steam exploded biomass using the Hartmann dust explosion equipment 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 [7]. The steam exploded biomass had finer particles due to their brittle fibres breaking up more easily [6] during the steam

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explosion process. In the present work the same steam exploded biomass was investigated using the ISO 1 m<sup>3</sup> dust explosion equipment. 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,  $K_{st} = \left(\frac{dp}{dt}\right)_{\max} V^{1/3}$ , were also determined.

The physics of flame propagation in pulverized biomass/coal burners are identical to that which occurs in spherical flame propagating pulverised biomass flames in explosions [9], so that the present work is not just about explosion hazards but also about flame propagation in pulverized fuel burners. Biofuels carry fire/explosibility risks in their handling [10,11] and there is little published information on this as the standard 1 m<sup>3</sup> explosion vessel with 'C' ring dust disperser does not work with fibrous biomass, 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 °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 be 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 Wong et al. [15] found that wood dust sizes up to 1200 µm 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 [16], using 20 L dust explosion vessel, have shown that the reactivity of Pittsburgh coal dust decreases with increase in particle size. They also reported that beyond 200 µm particle diameter, the coal dust was non-explosible for narrow size range distribution. However, for broad size range particle fraction, they were explosible due to the presence of fine particles. Gao et al. [17] studied the effect of particle size distribution on the propagation of the flame using Octadecanol dust. The flame was visualized by high speed camera combined with band width filter. It was concluded that the flame developed by fines was regular shape and continuous due to high release of the volatiles whereas the flame developed by coarse particles was discrete and discontinuous due to less release of volatile and burning of the solid particles. Flame imaging revealed that the flame colour changed to blue as the particle size varied from fine to coarse. Worsfold et al. reviewed the explosion sensitivity and severity of non-traditional dusts with emphasis on the nano-size particles in comparison to the micro-size particles [18]. 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 treatment 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 (fine), 63–150 µm (moderate), 150–300 µm (coarse) and 300–500 µm (very coarse). There was insufficient raw biomass supplied to undertake tests in the ISO 1 m<sup>3</sup> vessel, but the comparison with the raw pine wood and the steam exploded pine wood has been carried out using the Hartmann explosion equipment by Saeed et al. [7]. 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 tube. 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

Steam exploded pine wood was analysed for its elemental and proximate characterizations. Elemental analysis was performed using Flash 2000 thermoscientific analyser and proximate analysis using Shimadzu TA 50 [7]. By comparing raw pine wood and steam exploded pine (Table 1), elemental compositions were found to be similar, with a small increase in fixed carbon content and proportional reduction in volatiles in the steam exploded wood due to the previous thermal treatment. Steam exploded wood also had 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 defined (Fig. 1). The fineness of pine wood was increased after steam explosion treatment due to the shattering of structure and the increase in the brittleness of the particles. Also the increase in size fraction of this steam exploded pine wood (150–300 µm) approached to the same particle size distribution as that of raw pine wood.

### 2.3. Experimental methodology

Explosibility indices of the different studied fractions of steam exploded pine wood were determined with the modified ISO 1 m<sup>3</sup> vessel (Fig. 2). This vessel has a design pressure of 25 bar g to withstand and it was designed based on ISO 6184/1 standard. Details of this modified vessel and experimental methodology had been explained in previous works [19–22], besides repeatability of the tests were checked periodically for different samples and were found to be within allowable limits [23]. Different explosibility characteristics like turbulent and laminar flame speed, pressure

**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 (SEPW)
% 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
% H <sub>2</sub> O	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 <sup>3</sup> )	211.2	205
Bulk density (kg/m <sup>3</sup> )	629.0	436.7
True/particle density (kg/m <sup>3</sup> )	1678	1751.5

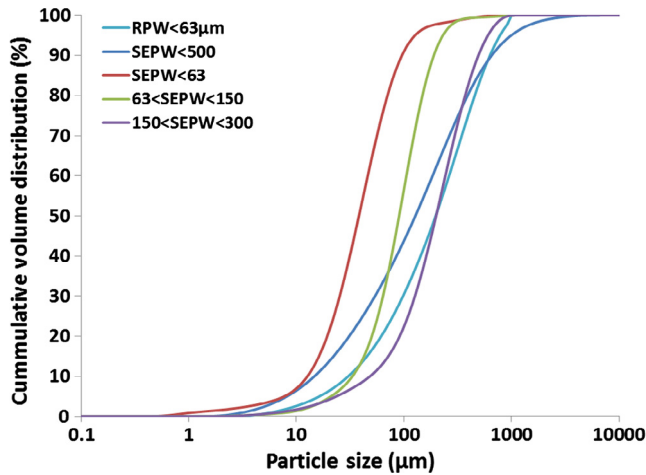


Fig. 1. Cumulative analysis of raw pine in comparison to its steam exploded sample of different sized fractions.

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 using Eqs. (1) and (2), by taking into account 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  $\pm 5\%$  for its estimation. For coarse sized fraction, the error is higher due to the partially burnt mass in the post explosion residues.

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

$$\text{Burnt equivalence ratio} = \frac{\text{Stoichiometric Air to Fuel by mass}}{\text{Actual Air to Fuel by mass}} \quad (2)$$

Coarse and fibrous samples presented several issues on dispersing with the standard C ring disperser, for which a calibrated hemispherical disperser with drilled pipe was used in the present study (Fig. 3). The drilled pipe, with an inside diameter of 20 mm and 3 mm wall thickness, had 9 holes of 6 mm inside diameter to have almost same flow area ( $254 \text{ mm}^2$ ) as in the standard C ring disperser ( $263 \text{ mm}^2$ ). The hemispherical cup diameter was selected

as 358 mm to accommodate enough amount of high voluminous biomass dust and calibration was performed using standard corn flour and Colombian coal samples. Explosibility results and residue mass left showed good comparison with an error of less than 5% for the most reactive concentrations. Additionally, the turbulence factor for this calibrated disperser was measured using turbulent to laminar flame speeds/turbulent to laminar deflagration indices ratio for 10% Methane determining a measured turbulence factor of 4.7, which was within the range of turbulence factors measured for standard C ring disperser [24–26].

### 3. Results and discussion

#### 3.1. Reactivity of steam exploded samples of different sized fractions

Reactivity of different size ranged steam exploded pine wood fractions were measured in terms of their 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 the limited amounts of sized fractions.

##### 3.1.1. Deflagration index vs. burnt equivalence ratio

Fig. 4 shows the deflagration index ( $K_{st}$ ) of different size ranged fractions of steam exploded pine wood against burnt equivalence ratio. It was observed that the finer the particles, the higher rate of propagation of flame and higher deflagration index the samples have. Also it was found that the least reactive concentration was leaner than the coarse fractions. The coarsest fraction did not explode even for  $1500 \text{ g/m}^3$  nominal concentration.

Flame development and propagation were mainly due to the release of volatiles that was happening with some delay due to the thicker particle surface of the coarse particles. Fine particles had more exposed surface area and they released higher volatiles yield efficiently resulting higher rate of pressure rise.

Fig. 4 shows the peak deflagration indices for the tested concentrations of these limited fractions, which are in the range of 43–122 bar m/s with the higher value for the fine fraction. Very coarse fraction of size range failed to ignite due to limited release of volatiles with existing concentration. The extrapolation curve fitting technique was applied using the results measurements that showed the possible trends of deflagration index against burnt equivalence ratio.



Fig. 2. Modified  $1 \text{ m}^3$  dust explosion vessel.



Fig. 3. Calibrated drilled pipe hemispherical disperser.



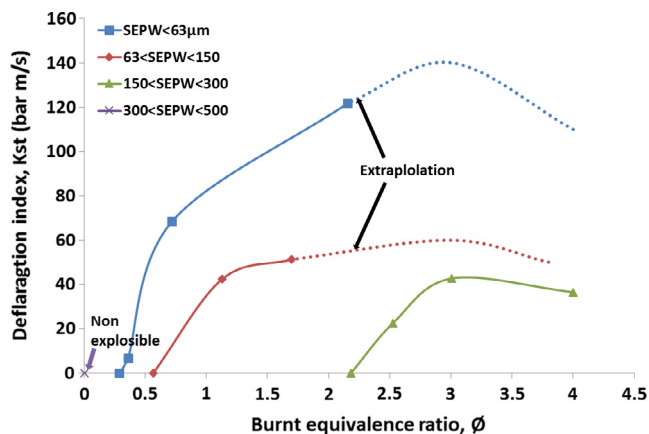


Fig. 4. Deflagration index ' $K_{st}$ ' vs. burnt equivalence ratio ' $\phi$ ' for different sized fractions steam exploded pine wood (SEPW).

### 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 the different sized fractions of steam exploded pine wood as shown in Fig. 5. It was noticed that the finer fraction burnt with a higher rise of pressure (8.6 bar with further rise for higher concentration (Extrapolated results) that could not be tested due to limited amount of dust) than the coarse fraction (7 bar) that was levelling at lower peak pressure ratio. Similarly the moderate size fraction presented the peak pressure ratio in between fine and coarse fractions, which means that the presence of fine facilitated the efficient propagation of flame with higher mass burning. Finally, the very coarse fraction could not turn to enough gas for the flame propagation.

### 3.1.3. Turbulent flame speed vs. burnt equivalence ratio

Turbulent flame speed variation was also plotted against burnt equivalence ratio as shown in Fig. 6. Flame speeds showed the same trend as deflagration index ( $K_{st}$ , Section 3.1.1) for the different studied burnt concentrations, presenting higher values for the fine fraction. These results show that a greater proportion of fines resulted in a quick release of volatiles with their maximum rate of combustion, while increasing the particle size caused a decrease on the values due to the delay in the evolution of volatiles from the coarse particles. Also the amount of mass needed for sustainment

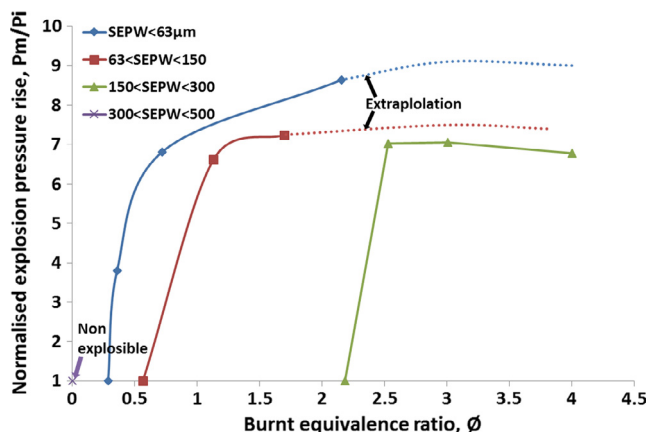


Fig. 5. Normalised explosion pressure ' $P_m/P_i$ ' vs. burnt equivalence ratio ' $\phi$ ' for different sized fractions steam exploded pine wood (SEPW).

and development of flame was increasing for the coarse size range fractions. The maximum flame speeds measured were in the range of 1.4–5.4 m/s with the higher flame speed for the fine size fraction. The flame speed results were extrapolated that showed the same trends as deflagration index against burnt equivalence ratio in Fig. 4.

## 3.2. Analysis of post explosion residues

### 3.2.1. Ultimate and proximate analysis of post explosion residues

Post explosion residues of the most reactive concentration from the different sizes were analysed and compared with raw steam exploded pine wood as shown in table 2.

It was found that the elemental analyses were similar for both studied samples, while significant differences appeared in the proximate analyses. It was observed that an addition of ash in the residue due to the proportion of mass burnt, which was forming combustion products of carbon dioxide and water. These products were discharged in the purging process leaving ash behind, which is the cause of this increase. Additionally, the finer the samples, the higher the amount of ash found in the post explosion residue due to the amount of mass burnt.

### 3.2.2. Surface morphological study

Scanning electron microscope images for the finer samples of the raw pine wood with its steam exploded and the post explosion residue sample were also compared as shown in Fig. 7. It was observed an 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 proximate analysis revealed the same unburnt mass as the original. For the coarse fraction, there were formation of holes 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 (see Fig. 7).

## 3.3. Comparison of modified ISO 1 m<sup>3</sup> and previous Hartmann results

A comparison of the results obtained with the modified Hartmann tube and with the 1 m<sup>3</sup> vessel showed the similarities existing between both methodologies, even so the rate of pressure rise in the 1 m<sup>3</sup> vessel was 6 times the one measured in the Hartmann tube due to the small diameter of the tube (see Fig. 8). Both methodologies showed that the most reactive concentration was at an equivalence ratio of around 1.8.

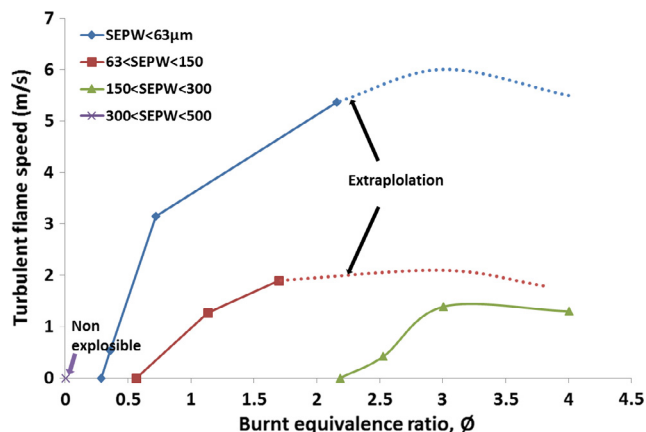
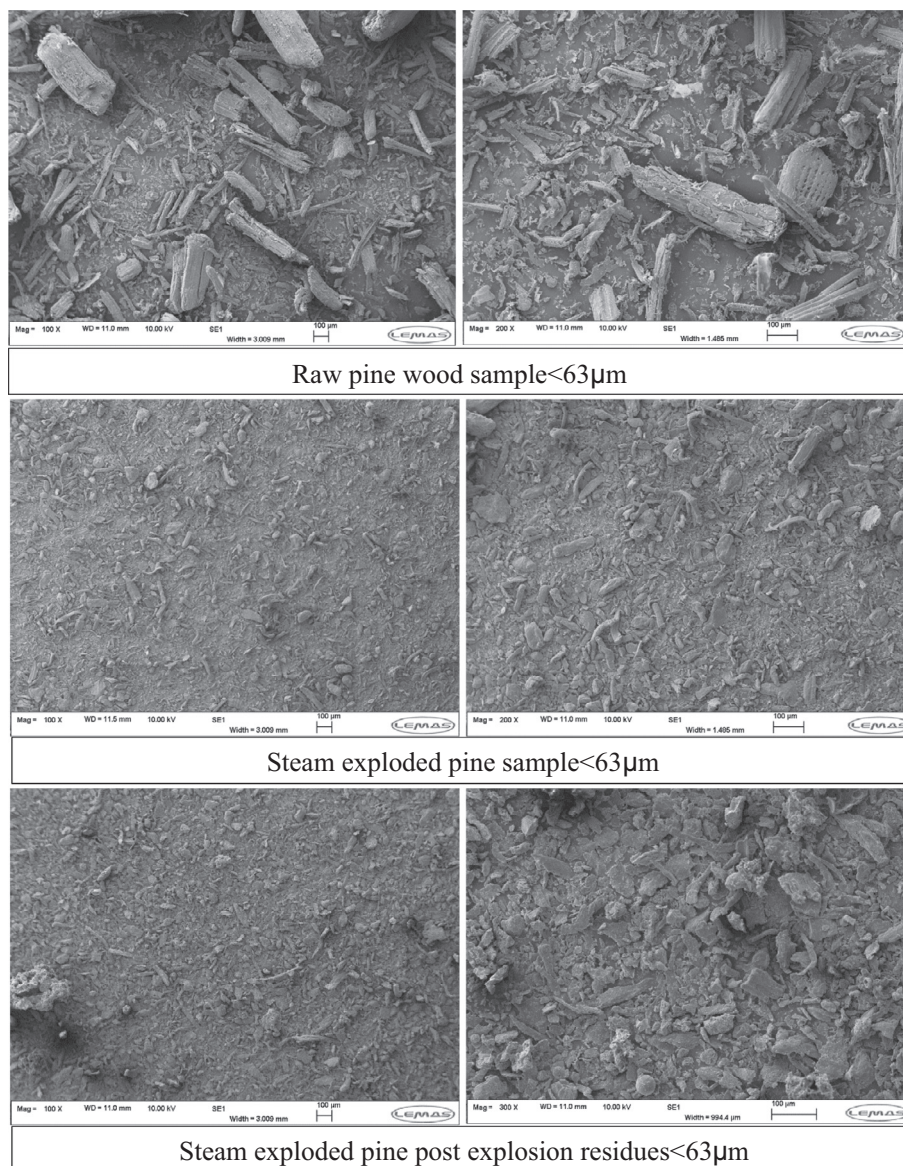


Fig. 6. Turbulent flame speed vs. burnt equivalence ratio ' $\phi$ ' for different sized fractions steam exploded pine wood (SEPW).

**Table 2**

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

Biomass	Steam exploded pine wood (SEPW)	Post explosion steam explosion residues		
		SEPW <63 $\mu\text{m}$	SEPW (63–150 $\mu\text{m}$ )	SEPW <500 $\mu\text{m}$
% 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
% H <sub>2</sub> O (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 <sup>3</sup> )	205	202.8	209.1	212.8

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

The effect of the mean particle size on the minimum explosive concentration of the studied steam exploded pine wood sample was plotted using 1m<sup>3</sup> measurements as shown in Fig. 9. It was

found that the minimum explosive concentration was increasing drastically for the higher mean particle size possibly due to less suspension time of thermally thick coarse particles. For small mean

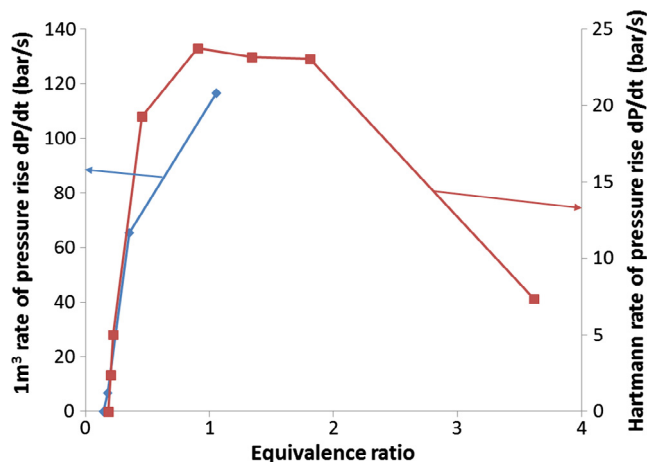


Fig. 8. Comparison of rate of pressure rise from 1 m<sup>3</sup> and Hartmann measurements against equivalence ratio for fine fraction of steam exploded pine wood <63 µm [7].

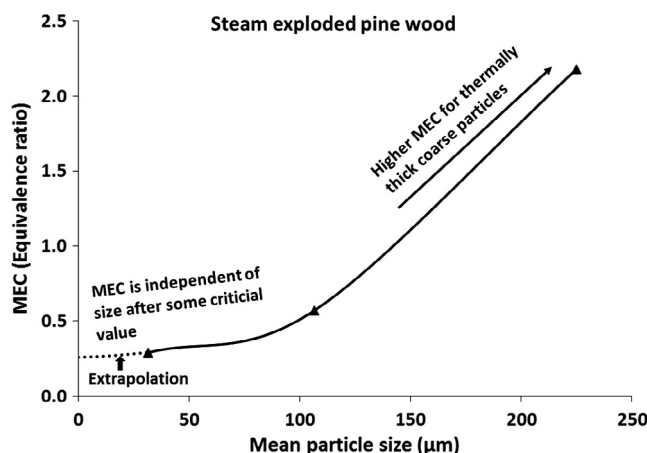


Fig. 9. Minimum explosive concentration measurements against equivalence ratio for average particle sizes of different steam exploded pine wood size range fractions.

particle size, the MEC was decreasing with declining slope. A critical point of mean particle size was reached after which the MEC was almost constant as predicted using extrapolation technique.

#### 4. Conclusions

In this work, different size range fractions of steam exploded pine wood were tested to investigate the flame propagation behaviour 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. Explosibility results concluded that samples with more amount of 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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