
Proceedings Paper:

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STEAM EXPLODED PINE WOOD: FLAME SPEED AND Kst AS A FUNCTION OF PARTICLE SIZE

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Contents

1. Introduction
2. Fire and Explosion Hazards Associated in the Handling of Pulverised Biomass Dusts
3. Characterisation of Biomass in Comparison to Coals
4. Modified 1m^3 explosion vessel with new calibrated disperser for coarse dust testing
5. Minimum Explosive Concentration in terms of Burnt Equivalence Ratio
6. Measurements of Explosibility Characteristics e.g.
    - 6.1 Deflagration Index (K_{st})
    - 6.2 Maximum Explosion Pressure (P_m/P_i)
    - 6.3 Turbulent Flame speed (s_{ft}) and Laminar Burning Velocity (u_L)
7. Post Explosion Analysis and Proposed Model for Coarse Particles Gasification
8. Conclusions

Introduction

- **Pulverised biomass woods, adopted in some Coal power generation plants, is one of the effective substitute of the pulverised coal to cope with the environmental regulations in reducing the GHG's for green environment.**
- **In the UK pulverized woody biomass burning in existing coal fired power stations generated 5.7% of electricity in 2014.**
- **However, these biofuels have low bulk densities and low calorific values, that make its handling and transportation a challenge.**
- **Adoption of thermal pre-treatment helps to make the particles easier to mill, increases the bulk density and increases the CV by around 10%.**
- **One of thermal treatment techniques – steam explosion – had samples evaluated for their reactivity in the present work.**

- The transport issues of biomass fuels has led to their use in green power generation being predominantly in the form of pellets. These are pulverised biomass that has been dried to <10% and compressed into pellets of about 5mm diameter and 20mm long.
- These pre-treatments increase the bulk density and decrease the water content, which minimizes the transportation costs as a greater mass or energy content can be carried for a given ship or lorry load volume.
- Further pretreatment of biofuels have been advocated by several research groups and various pilot plants exist to develop these materials.
- The processes involved in the pretreatment of biofuels are generally commercially confidential but split into two areas: Torrefaction and Steam Exploded Biomass. The product is sometimes referred to as ‘Biocoal’ and this product is also sometimes referred to as ‘black pellets’.

- **Torrefied biomass involves heating at around 260 – 320°C, then pulverisation and compression into pellets.**
- **Steam exploded biomass involves heating to similar temperatures with hot steam at high pressure and then releasing this pressure so that the water absorbed in the biomass ‘explodes’ out, shattering the biomass.**
- **Steam exploded biomass is often referred to as ‘black pellets’ as the pellets are black.**
- **An important feature of torrefied biomass and steam exploded biomass is that the fibrous nature of woody biomass becomes brittle and the biomass is then much easier to pulverise.**
- **These biocoals can be pulverised alongside coal in the same mills and do not need to be pre-pulverised prior to biocoal processing,**
- **They have a higher bulk density, higher CV, lower water and lower transportation costs.**
- **The treatment of biofuels this way is then pelletised and these are usually impervious to water and can be stored in the open.**

Contents

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- **Biomass dust is utilized in pulverised form for their efficient and effective combustion. This pulverised dust form has fire and explosibility hazards associated with them that need to be contained in the safe working boundaries for safety.**

A very recent incident of wood floor mill explosion in UK (17 July 2015) was reported with physical and human loss (4 deaths were reported).

- **Some recent incidents related to biomass dust explosions are given below as examples.**
- **Krabi biomass power plant [April 8, 2015]**

  Two workers injured due to massive fire. Damage was estimated at about Bt 100 million (Source: The Nation News, 2015).
- **Biomass power plant managed by Eco Sustainable Solution Ltd. at Southampton dock[January 03, 2015]**

  No injury. 20 ft flame and thick cloud of billowing smoke due to woodchip pile fire was seen (Source: Southern Daily Echo, 2015).

- **Fire and then explosion at Jaffrey, N.H., manufacturing plant, New England Wood Pellet LLC [October, 2011]**

  It took 100 fire fighters and 15 hours to put down the fire. The company had to pay fine of $100,000 (Source: Fitzgerald and Bowser, 2011).

- **Explosion at the RWE's 750,000 ton wood pellet factory, Georgia, USA [June, 2011]**

  An overheated roller/bearing assembly in a pelletizer sparked the blast at the factory (Source: Renewables-International-Magazine, 2011).

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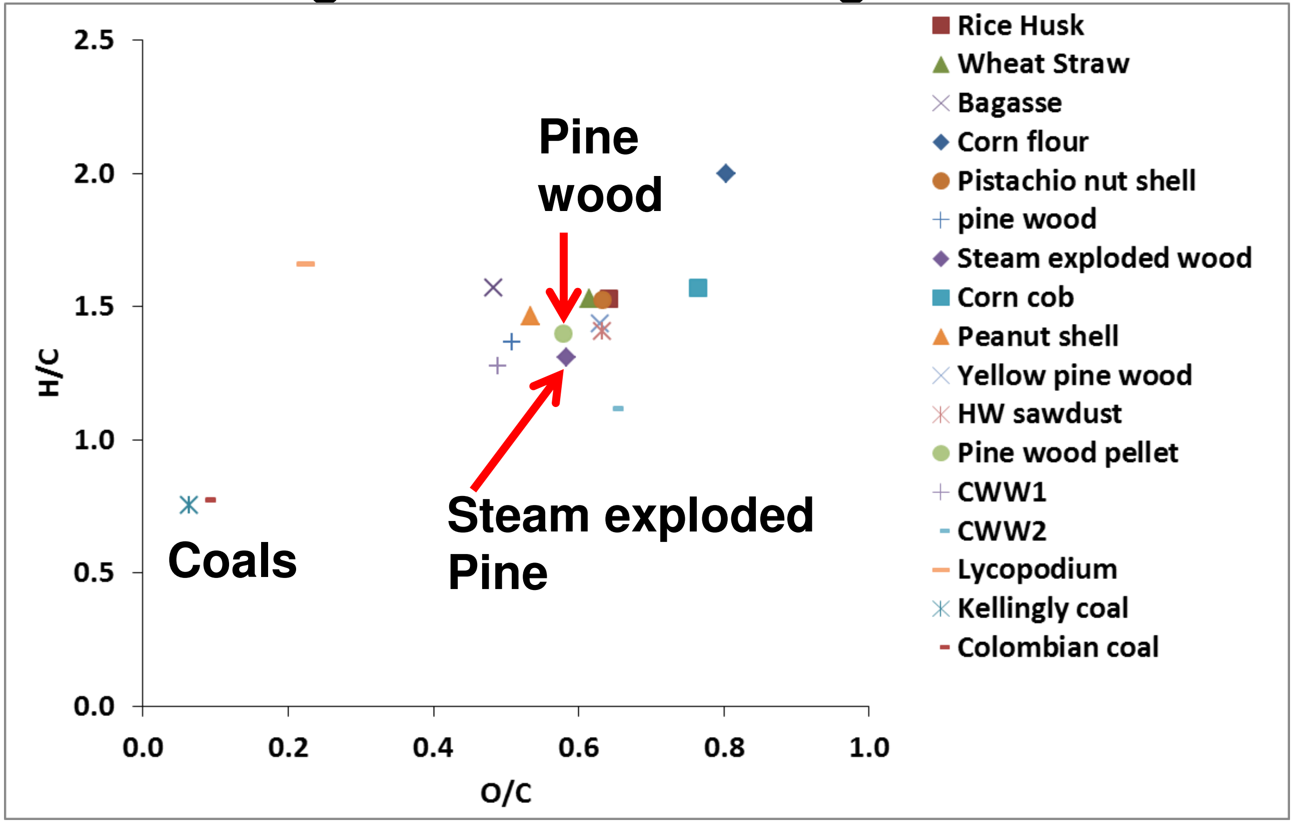
EFFECT OF STEAM EXPLODED TREATMENT ON THE REACTIVITY OF PINE WOOD.

M.A. Saeed, G.E. Andrews, H.N. Phylaktou & B.M. Gibbs, ERI, SCAPE, University of Leeds, UK

	Yellow pine wood (YPW)	Steam exploded wood (BP)	Kellingley Coal	Colombian Coal
% C	51.0	52.8	82.1	81.7
% H	6.1	5.8	5.2	5.3
% N	0.0	0.4	2.97	2.6
% S	0.0	0.0	2.8	0.86
% O	42.9	41.0	6.96	9.6
% H_2O	5.4	4.4	1.7	3.2
% VM	77.5	73.0	29.2	33.7
% FC	15.3	19.9	50.0	47.8
% Ash	1.7	2.7	19.1	15.3
CV (MJ/Kg)	19.9	19.5	25.0	26.4
Stoich. A/F (g/g)	6.12	6.3	11.6	11.2

- Biomass dusts have inherent oxygen in their structure with higher volatile contents that release in the lower temperature range assisting the efficient burning.



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

Steam exploded pine has a very similar O/C as the original pine but there was a small reduction in the H/C.
There was only a small difference in the stoichiometric A/F.
Biocoal is chemically similar to the parent biomass and quite different to coal.
The term 'biocoal' refers to the dark appearance and its brittleness.

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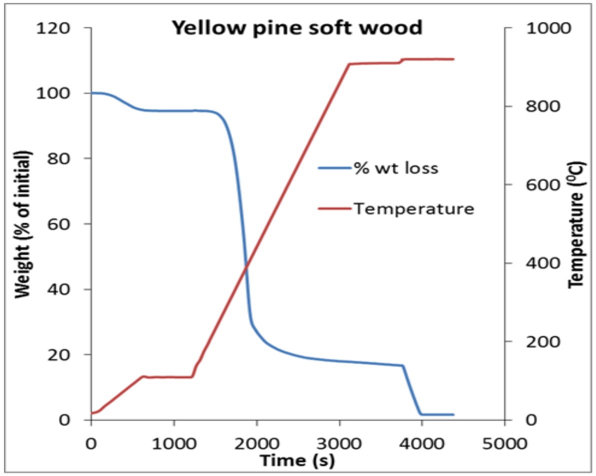
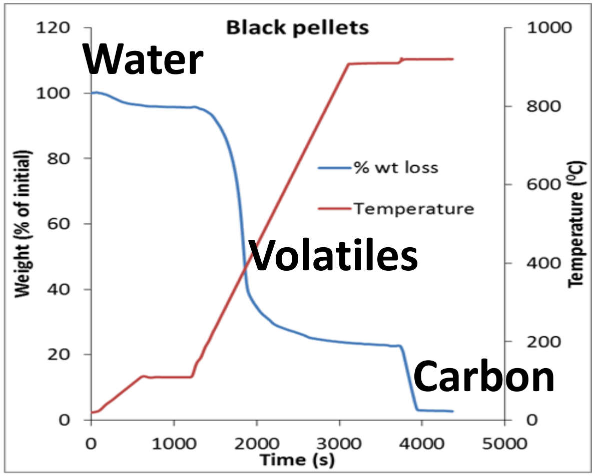
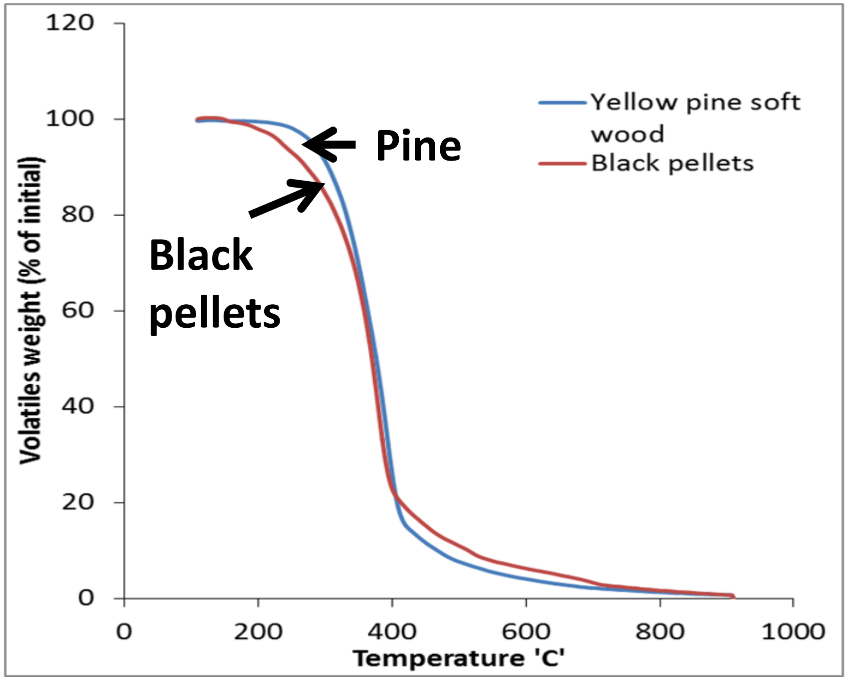


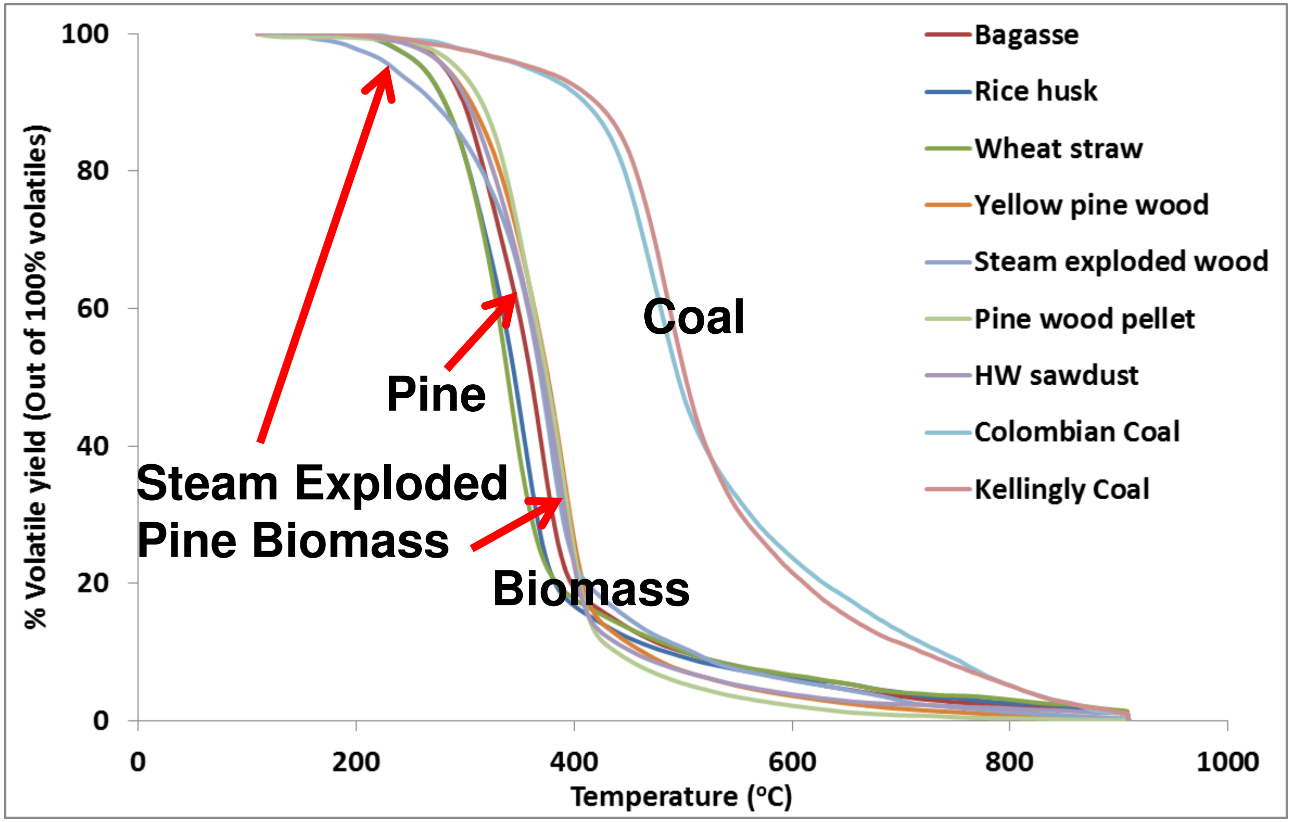


TGA analysis of pine and Steam exploded biomass (black pellets). Heating in N_2 up to 900°C and then oxidation in air.



Steam exploded biomass has an earlier release of volatiles in the 200 – 300°C region and a slightly later volatile release above 300°C.
Overall the volatiles are released over a wider temperature window.
The earlier release of volatiles Should make the steam exploded biomass more reactive than the raw pine biomass.

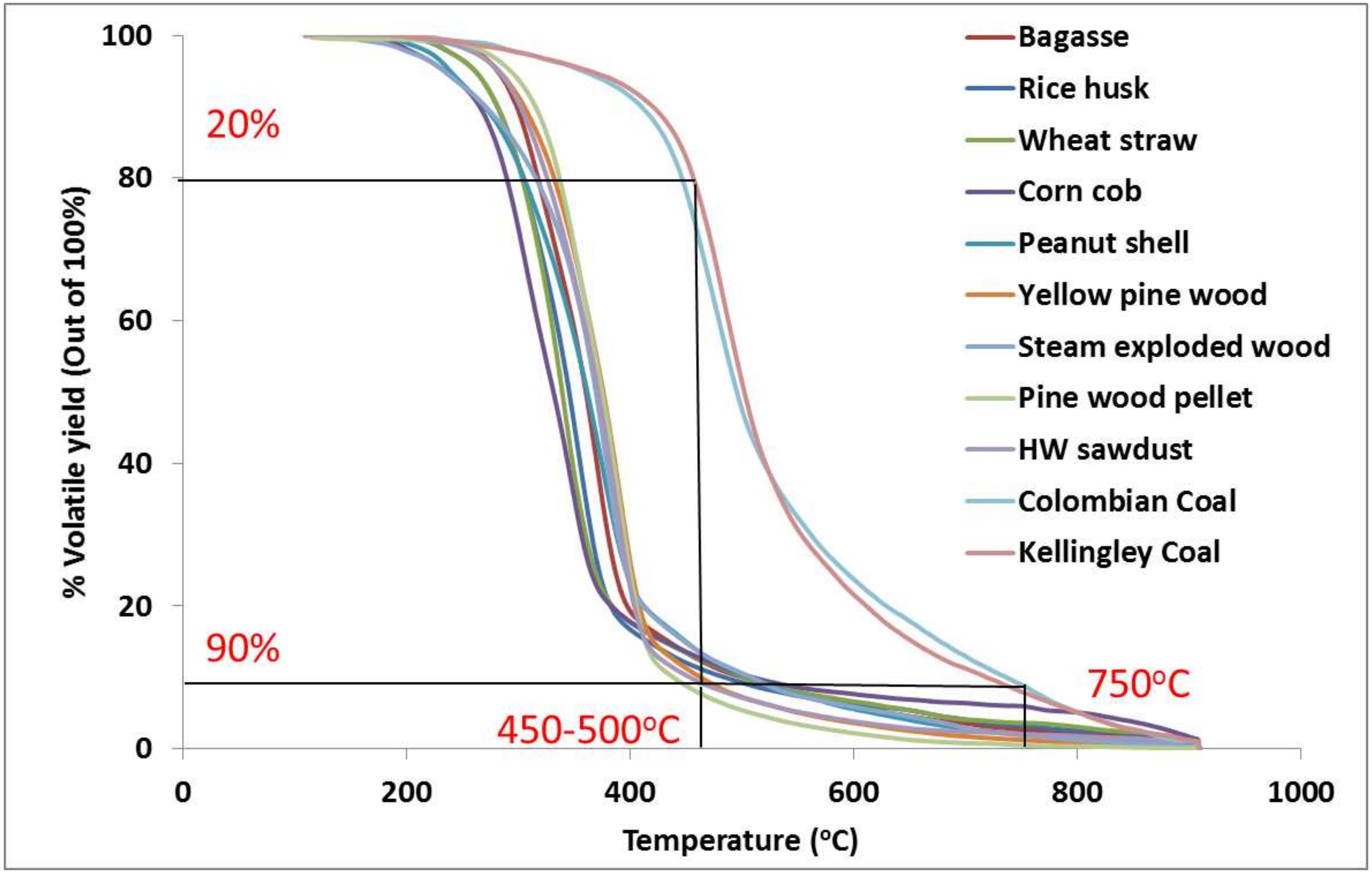
- **Biomass dusts have inherent oxygen in their structure with higher volatile content that release in a lower temperature range than coal.**



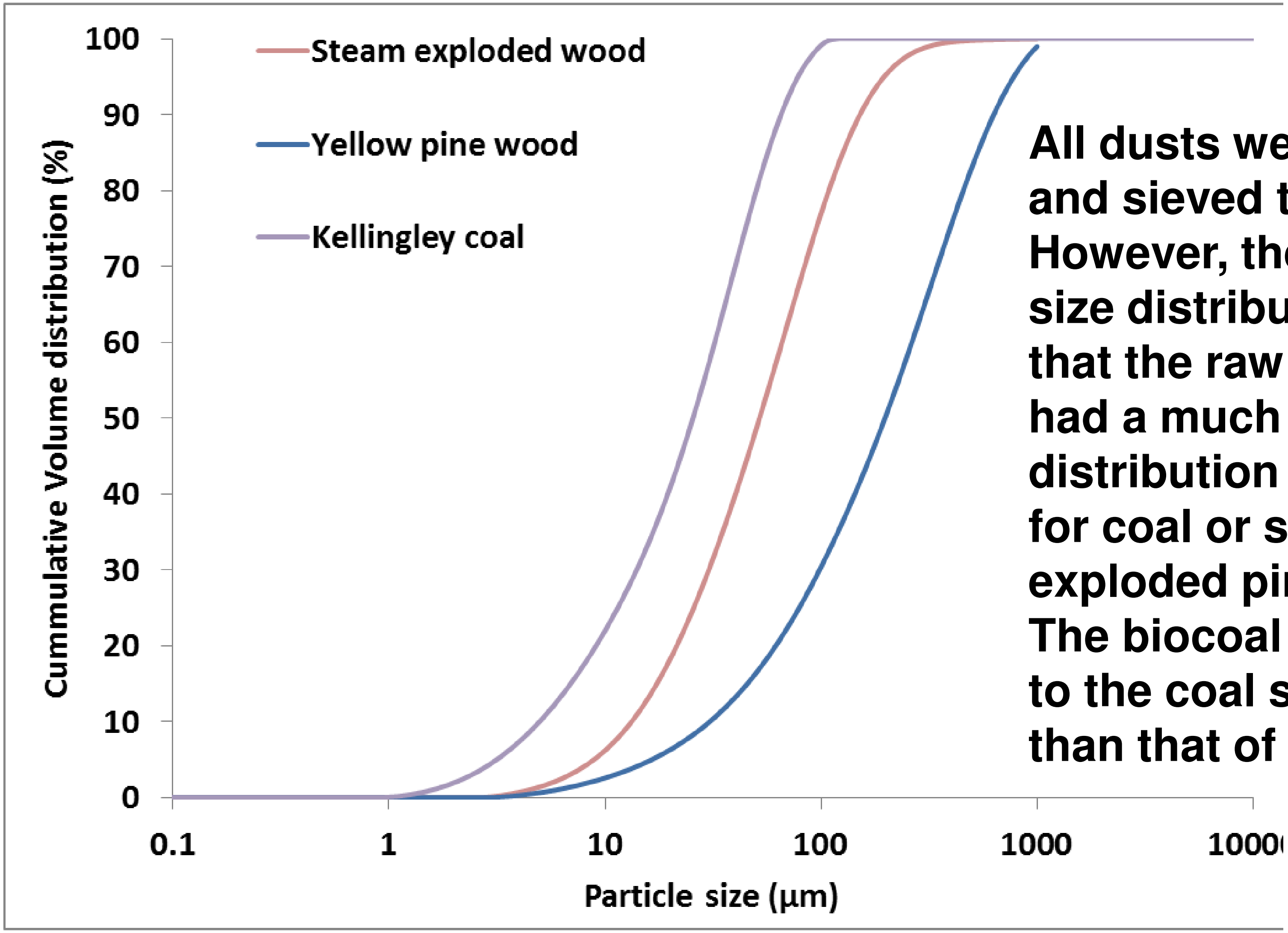
% loss of volatiles as a function of temperature

Biomass not only has much higher volatile content than coal but the volatiles are released at lower temperatures. 70% of the volatiles are released between 300 and 400°C. The biomass used in this work are similar to other biomass Investigated by the authors.

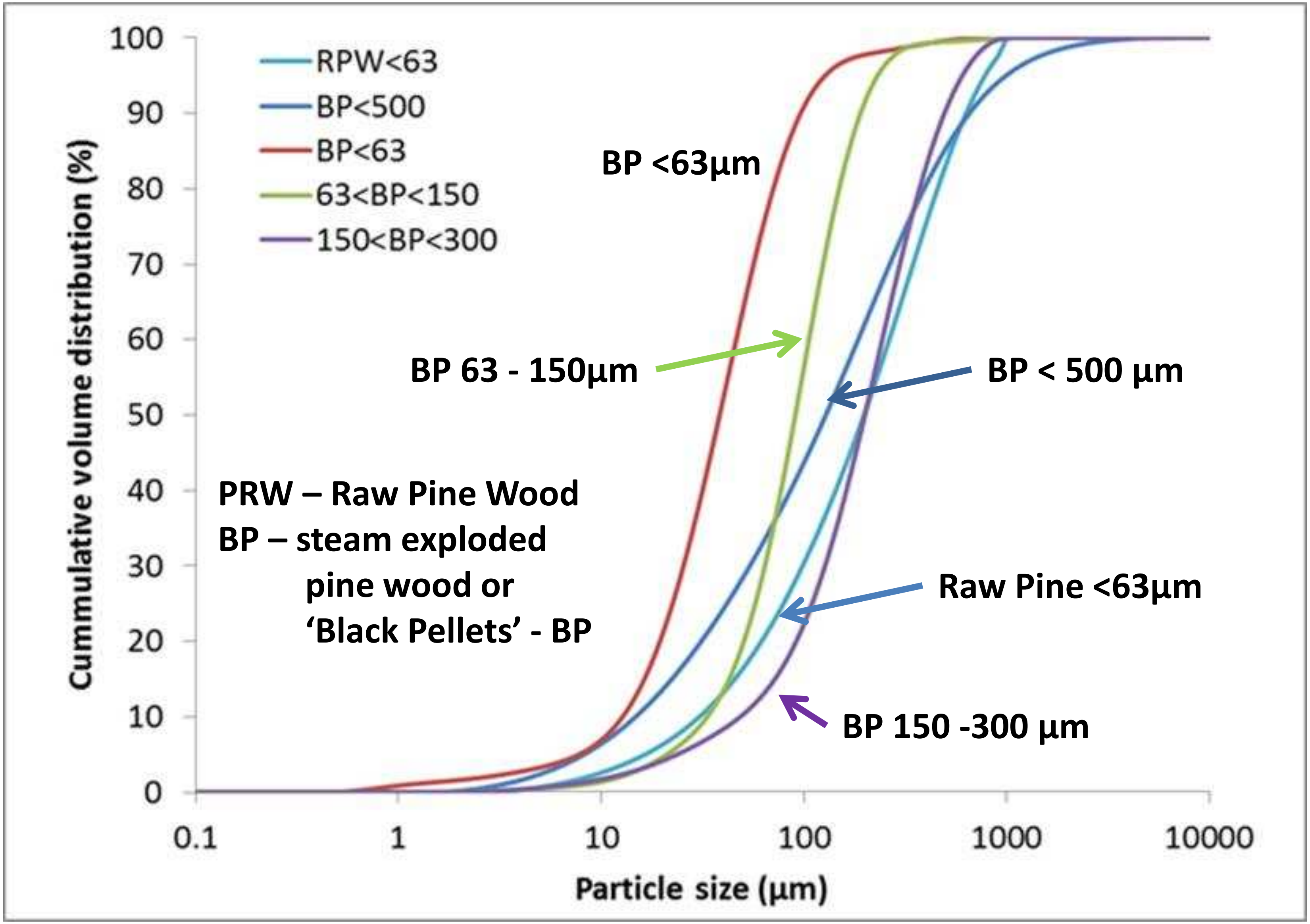
- **Biomass dusts also have higher volatile contents that release in the lower temperature range assisting their efficient burning compared to coals.**



Particle size distribution for the raw pine and the steam exploded pine.



All dusts were milled and sieved to <63µm. However, the particle size distribution shows that the raw pine wood had a much larger size distribution range than for coal or steam exploded pine.
The biocoal was closer to the coal size distribution than that of the raw pine.



PRW – Raw Pine Wood
BP – steam exploded
pine wood or
'Black Pellets' - BP

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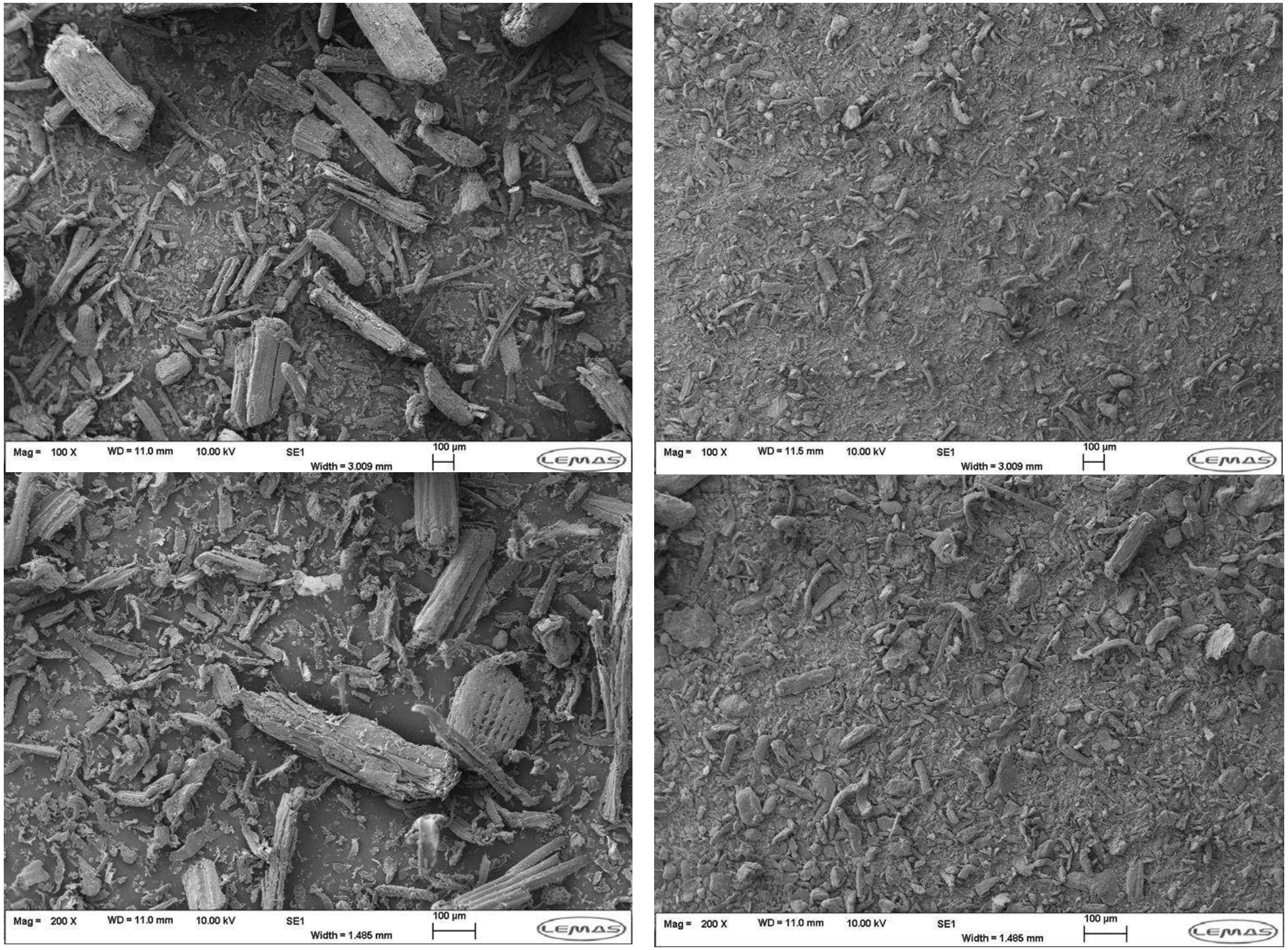

Yellow pine wood

Seam exploded black pellet

SEM images of the raw pine wood and steam exploded black pellet

In the present work we had insufficient of the raw pine wood supplied by the steam exploded biomass (Black Pellets – BP) manufactures to carry out explosions in the ISO 1 m^3 equipment for different particle sizes. Thus the present results are only for the steam exploded biomass in terms of the influence of particle size.
However, we had sufficient raw pine wood to carry out tests of the <63µm sample on the Hartmann equipment, which has been published previously and is included here for comparison

These previous results show that there were signficantly smaller particles in the steam exploded biomass and this was found to dominate the differences in the explosion properties.

Contents

1. **Introduction**
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3. **Characterisation of Biomass in Comparison to Coals**
4. **ISO 1m^3 explosion vessel with new calibrated disperser for coarse dust testing**
5. **Minimum Explosive Concentration in terms of Burnt Equivalence Ratio**
6. **Measurements of Explosibility Characteristics e.g.**
   - **6.1 Deflagration Index (K_{st})**
   - **6.2 Maximum Explosion Pressure (P_m/P_i)**
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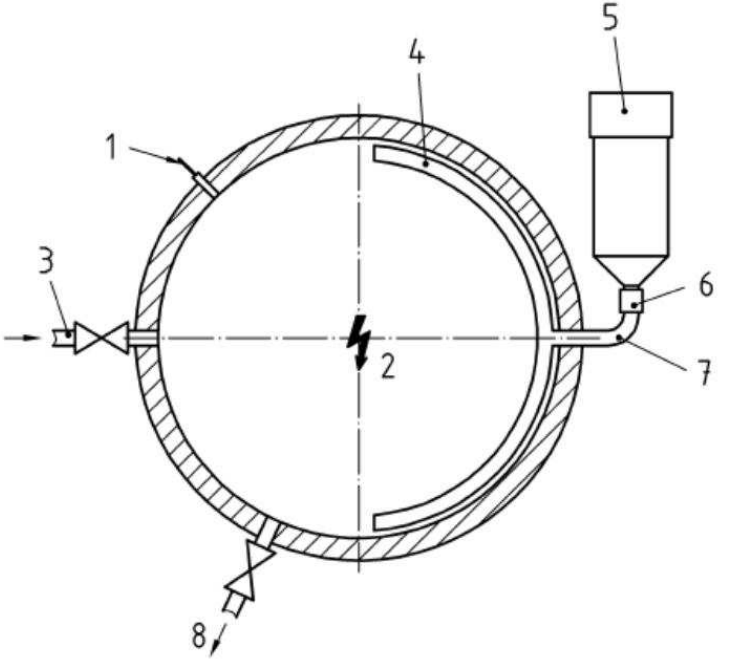
ISO 1m^3 Vessel

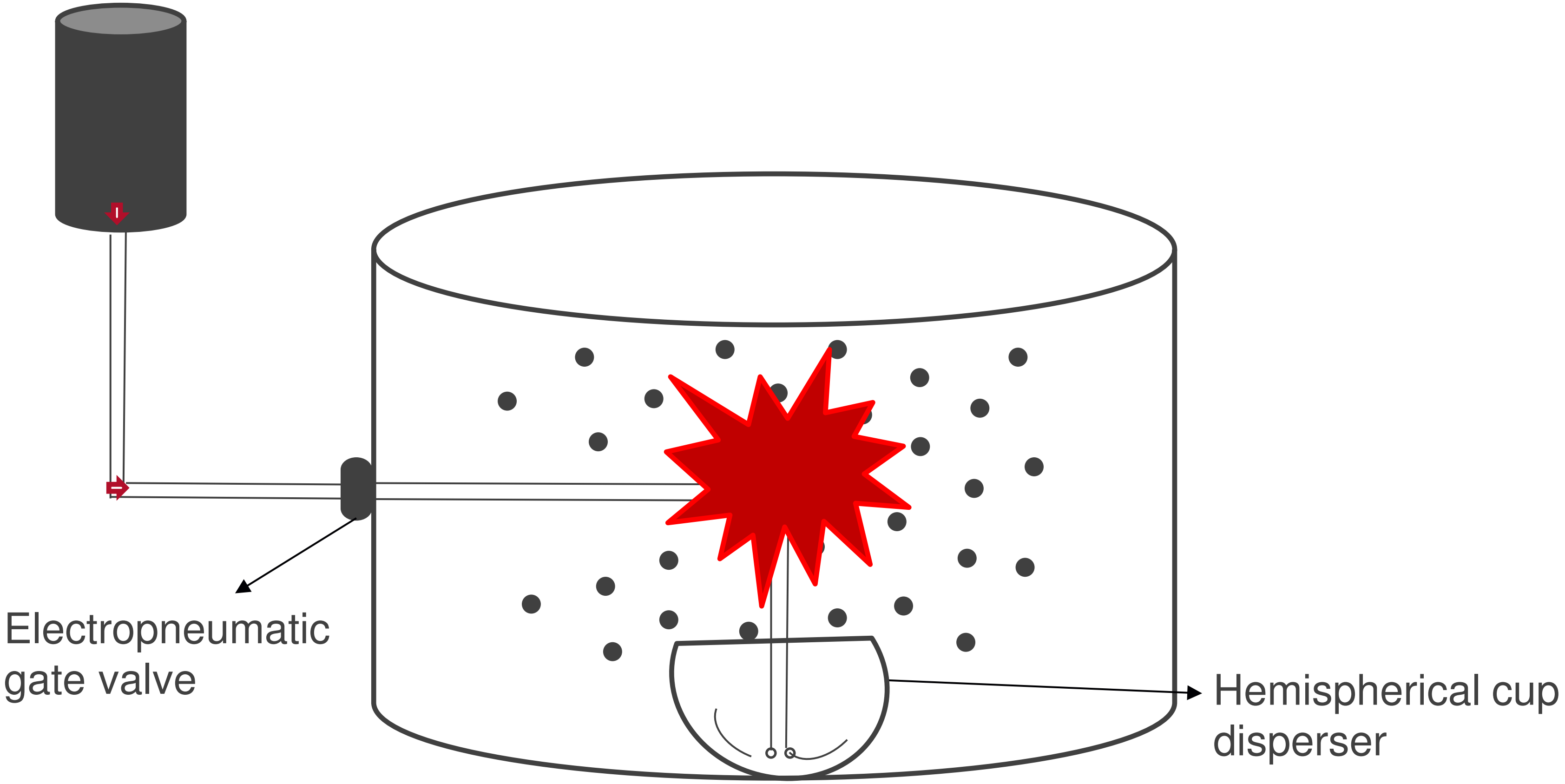
- ISO 1m^3 dust explosion vessel utilizes a 5L external dust pot through which the dust is pneumatically dispersed using a C-ring disperser.
- The dust cloud is then ignited using a 10kJ chemical igniters connected with electrodes placed at the centre.
- Two (5kJ each) chemical igniters are activated with pre-set optimum ignition delay of 0.6s for C-ring disperser.
- Vessel was initially vacuumed so that the resultant pressure after the discharge of dust pot is atmospheric just before the ignition.
- Two pressure sensors record the rise of pressure due to explosion.



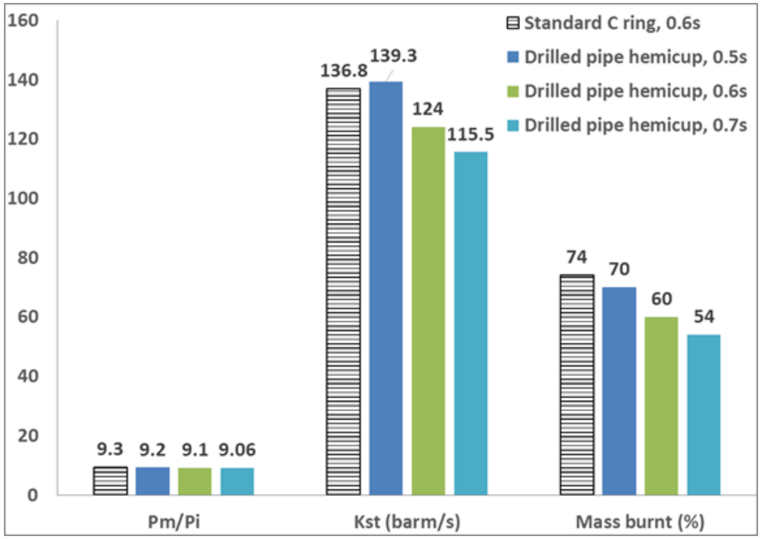
1) pressure sensor
2) chemical igniters
3) inlet for purge air
4) dust disperser
5) dust container
6) fast acting valve
7) connecting tube
8) outlet for exhaust gas

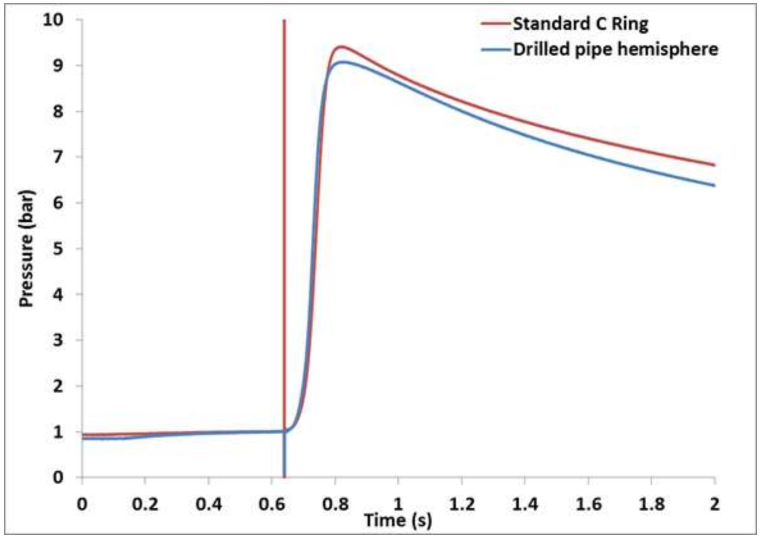
- **5L std. dust pot was extended with another 5L pot for low density fuels especially voluminous biomass.**
- **Hemispherical disperser was calibrated using standard corn flour and Colombian coal samples based on explosibility parameters and the mass burnt.**
- **The turbulence factor for this calibrated disperser was found to be a little higher than std. C ring to apply enough shearing force to lift the particles.**

Dust is placed in the hemispherical-cup instead of external pot that can utilize its use for the testing of fibrous and coarse biomasses.

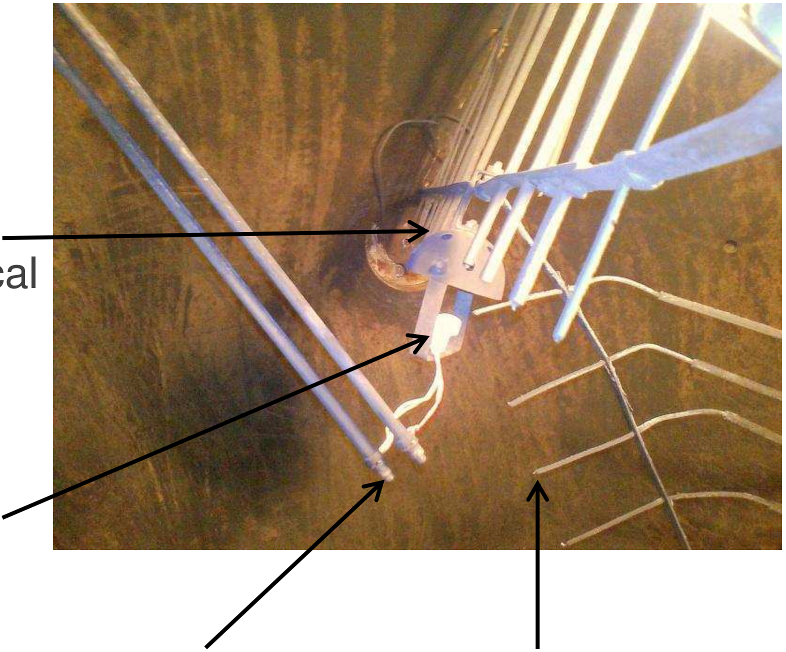


	Calibrated Hemispherical cup disperser	**Standard C-ring disperser**
Ignition delay (s)	**0.5s**	**0.6s**
Valve off timing (s)	**0.64s**	**0.65s**
Dispersion pressure (bar,g)	**20bar for 10L**	**20bar for 5L**
	10% Methane ($Turbulence\ factor = \frac{K_{g,turbulence}}{K_{g,laminar}}$)	
Turbulence factor	**4.7**	**4.0**





- **2D arrays of thermocouples were used to measure the time of flame arrival for flame speed measurements and to determine the uniformity of the dust cloud.**

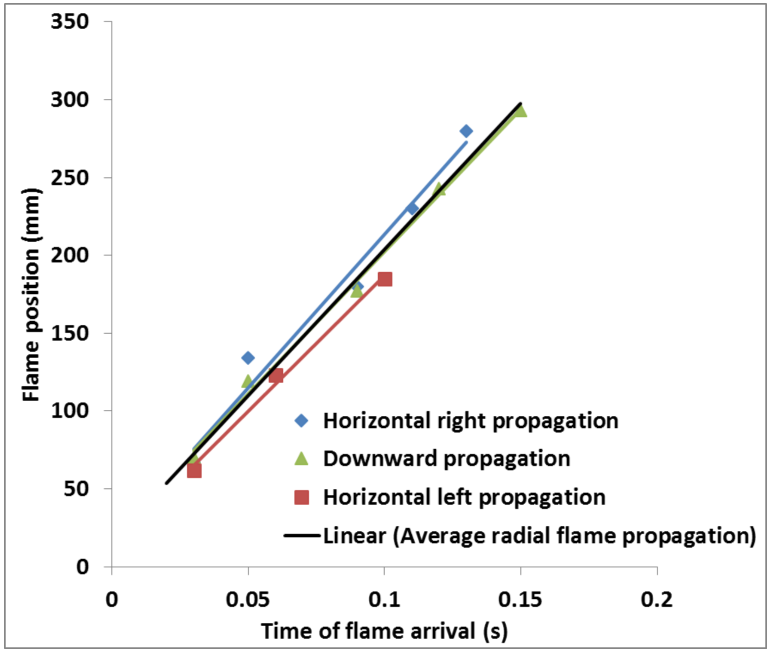


Hemispherical cup for spherical flame

Chemical igniters (10kJ)

Electrodes

Exposed junction K-type thermocouples



Contents

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- **In past, the concentration of the solid dusts have been reported in terms of ‘g/m^3’. It is preferable to express the dust concentration as an equivalence ratio, as is done in all gas explosion research.**
- **It is found in the ISO 1 m^3 equipment that a significant fraction of the dust injected is found on the floor of the vessel at the end of the test. This has not participated in the explosion and analysis of the debris shows that it is mostly the original dust with the same composition and same size distribution.**
- **The equivalence ratio for the misture that burnt is derived from the measured mass of the explosion residue.**

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

$$Burnt\ equivalence\ ratio, \emptyset_{burnt} = \frac{(\frac{Air}{Fuel})_{Stoichiometric}}{(\frac{Air}{Fuel})_{Acutal}} \quad (by\ mass) \qquad (2)$$

- **Most HC's fuels have their lean flammability limits half of their stoichiometric concentration.**
- **Oxy-fuels like biomasses were found to have their MEC much leaner that for hydrocarbons.**

Gas/Dust	A/F Ø=1	daf. g/m^3 Ø=1	MEC Ø	Method	Gas/Dust	A/F Ø=1	daf. g/m^3 Ø=1	MEC Ø	Method
Methane	17.2	70	0.46	EU Tube [1]	Torrefied Wood	7.17	167	0.20	Hartmann [22]
Propane	15.7	76	0.43	Tube [19]	Torrefied Norway Spruce	6.61 8.70	181 138	0.17 0.22	Hartmann [22]
Ethylene	14.8	90	0.38	EU Tube [1]	Wood 95 µm	5.63	213	0.14	1 m^3 [21]
Polyethylene	14.8	81	0.25 0.37	Hartmann [13] 1 m^3 [6]	Bark 57 µm	6.03	199	0.14	1 m^3 [21]
n-Hexane	15.2	79	0.46	EU Tube [1]	Forest Residue 102 µm	4.78	251	0.22	1 m^3 [21]
1,3,5 TMB $70\ ^0C$			0.50	EU Tube [1]	Bagasse	6.45	186	0.27	Hartmann [23]
Hydrogen	34.5	34.8	0.12	Tube [19]	Rice Husks	6.24	192	0.35	Hartmann [23]
CO	3.45	350	0.41	Tube [20]	Wheat Straw	6.03	199	0.55	Hartmann [23]

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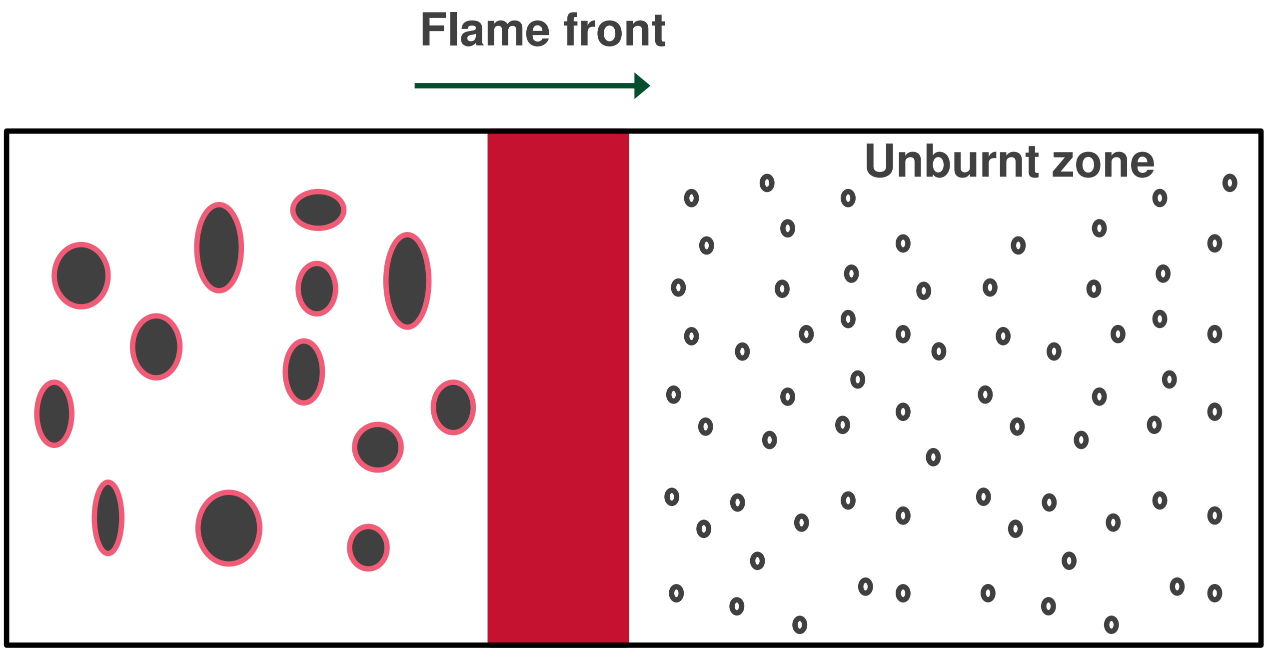
Material	A/F at Ø=1	g/m^3 at Ø=1	MEC Ø	MEC g/m^3	Method
Yellow Pine	6.1	211	0.39	82	Hartmann
Steam Exploded Yellow Pine	6.3	206	0.20	41	Hartmann
Columbian Coal	11.2	107	0.39		Hartmann
Columbian Coal	11.2	107	0.43	46	1 m^3
Polyethylene	14.8	81	0.37	30	Hartmann
Propane	15.7	76	0.43	33	EU Tube

The main reason for the leaner MEC for steam exploded yellow pine was the much smaller particle size, shown earlier. This gives a greater surface area for oxidation reactions and for the release of volatiles. The chemical changes In the steam exploded biomass process were small and it was the physical destruction of the fibrous nature of woody biomass that was most important.

- **The ISO $1m^3$ MEC of steam exploded pine wood was $\emptyset_{\mathbf{burnt}} = \mathbf{0.29\ for < 63\mu m}$ than the fine coal samples.**
- **However for the coarse size fractions, the MEC increased depending on the proportions of fine size particles in the coarse size range fraction.**
- **A model for the coarse dust flame propagation that explains this effect is that the flame propagates in the fines and that the coarse particles in the explosion induced wind ahead of the flame, lag behind the fines and are heated in the burnt gases and for rich mixtures are gasified.**
- **For coarse dusts the fraction of fines is reduced and the mixture must be richer overall for the fine fraction to be flammable.**



Coarse particles lagging
and gasifying behind flame

Fine particles
ahead of flame

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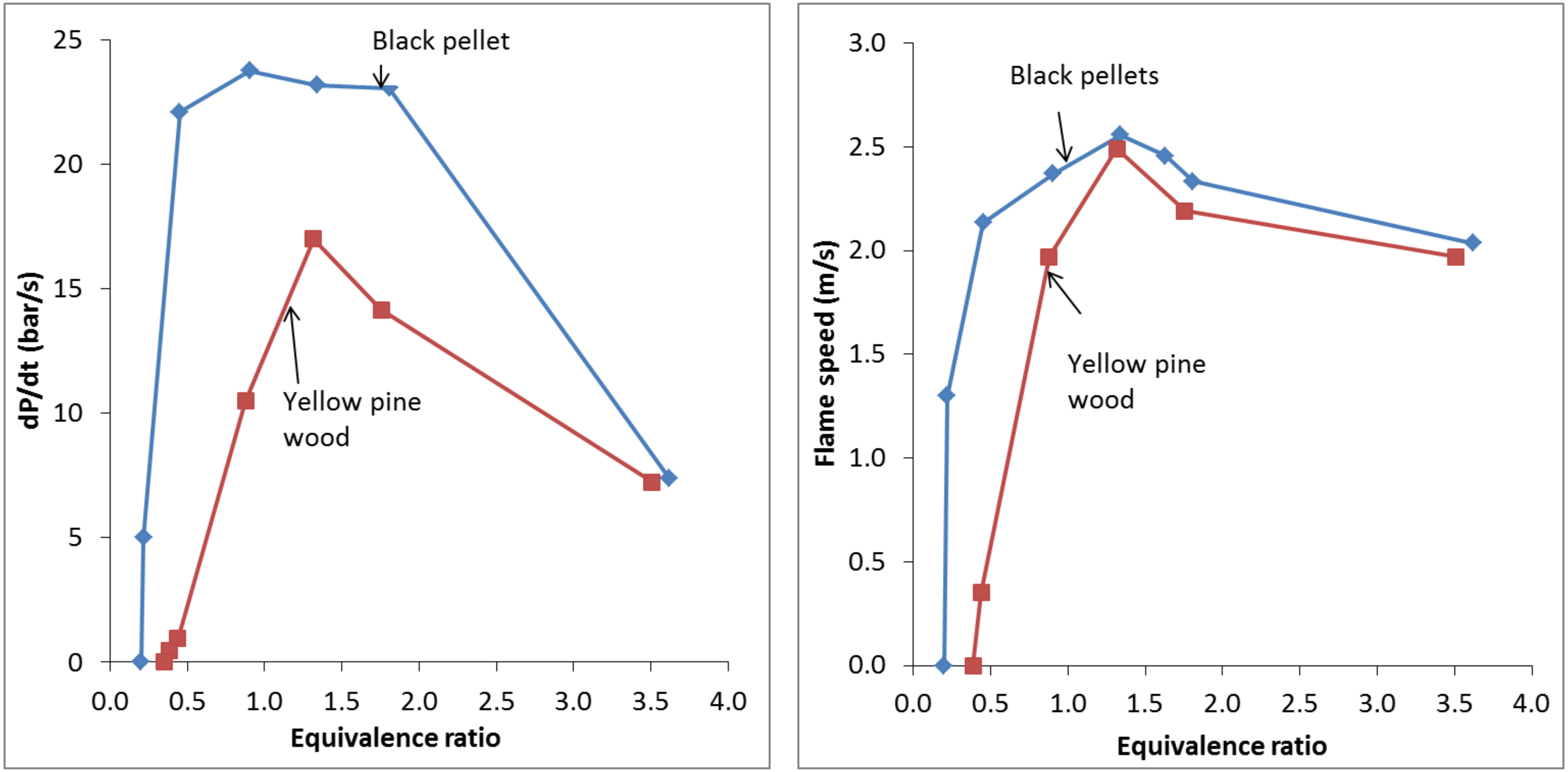
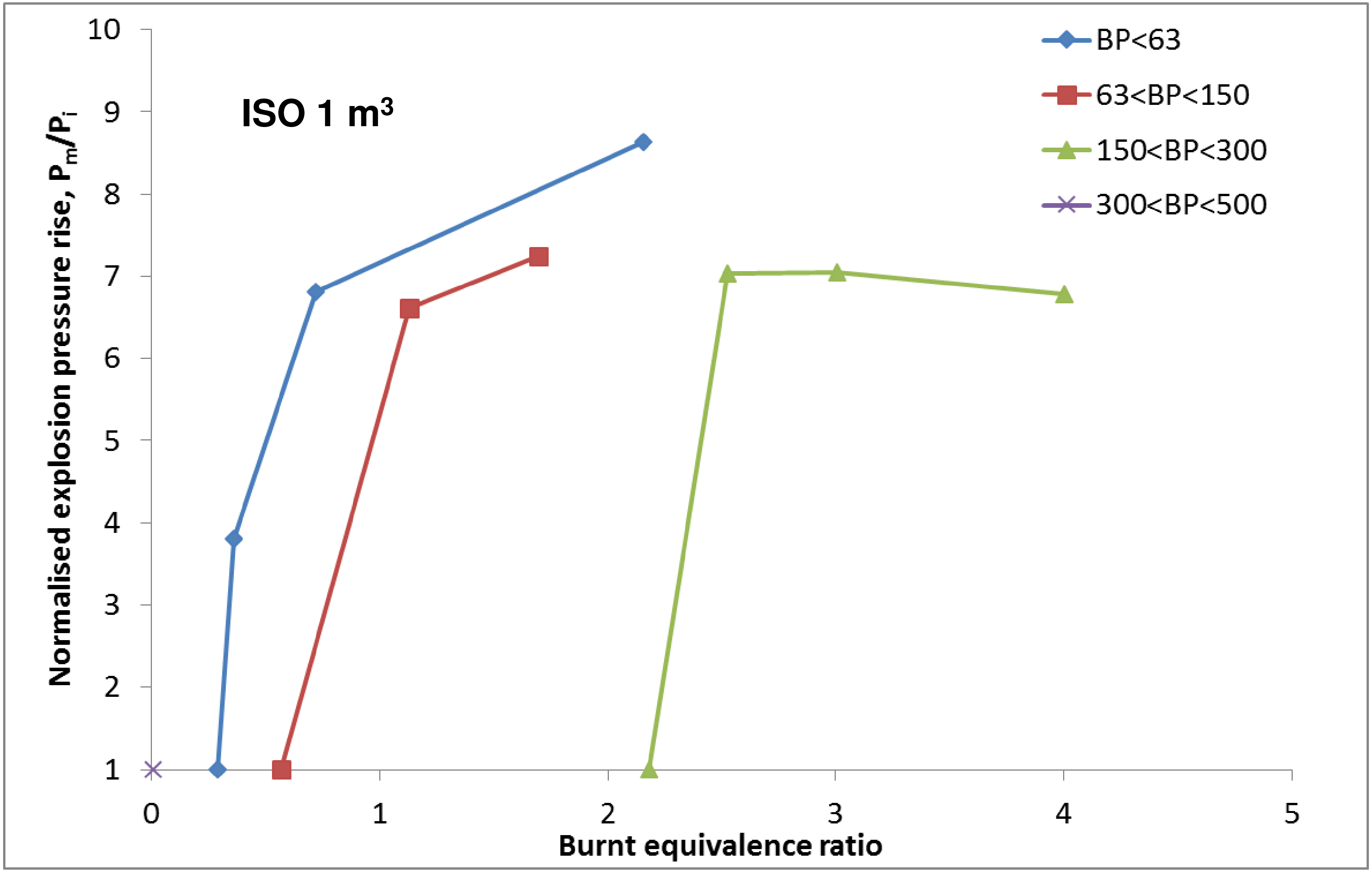
Hartmann explosion tube



Rate of pressure rise and flame speed as a function of equivalence ratio.

Note the much leaner burning region for steam exploded biomass (black pellets compared with the raw yellow pine.


ISO 1 m³
Normalised explosion pressure rise, P_m/P_i
Burnt equivalence ratio
BP<63
63<BP<150
150<BP<300
300<BP<500
10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5

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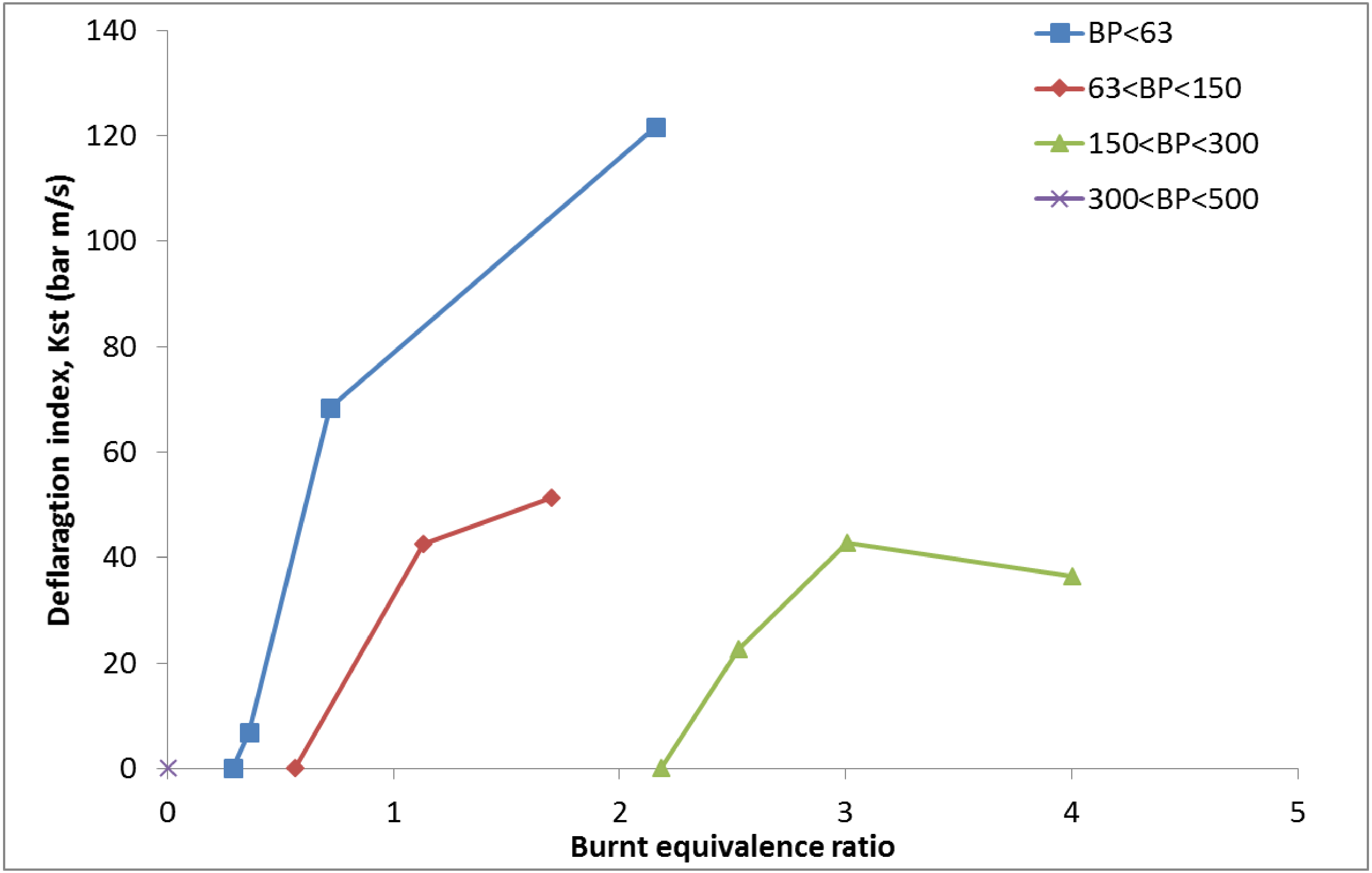

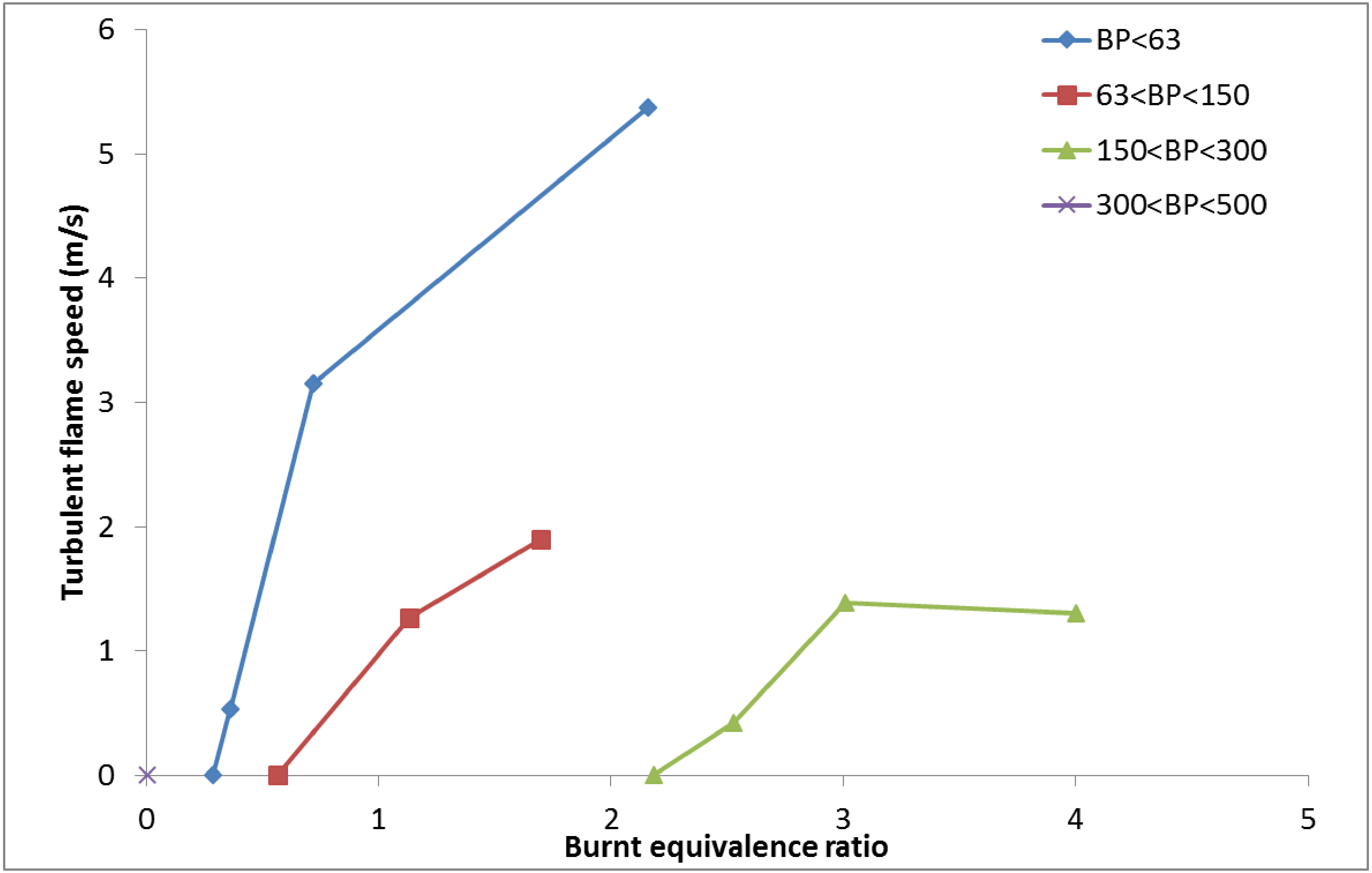
6
5
4
3
2
1
0
Turbulent flame speed (m/s)
0
1
2
3
4
5
Burnt equivalence ratio
BP<63
63<BP<150
150<BP<300
300<BP<500

- The maximum explosion pressure of fine steam exploded wood was comparable to the fine coal samples (~8.6 bar) and for coarse size range fractions were above 7bar.

- The deflagration index, K_{st}, was also found to be a strong function of particle size with the higher value (122 bar m/s) for the finer fraction (<63µm) and lower values (~43 bar m/s) for the coarse fraction (150-300µm).

- The peak turbulent flame speed of steam exploded pine were around 1.4-5.4 m/s depending on the proportion of fines.

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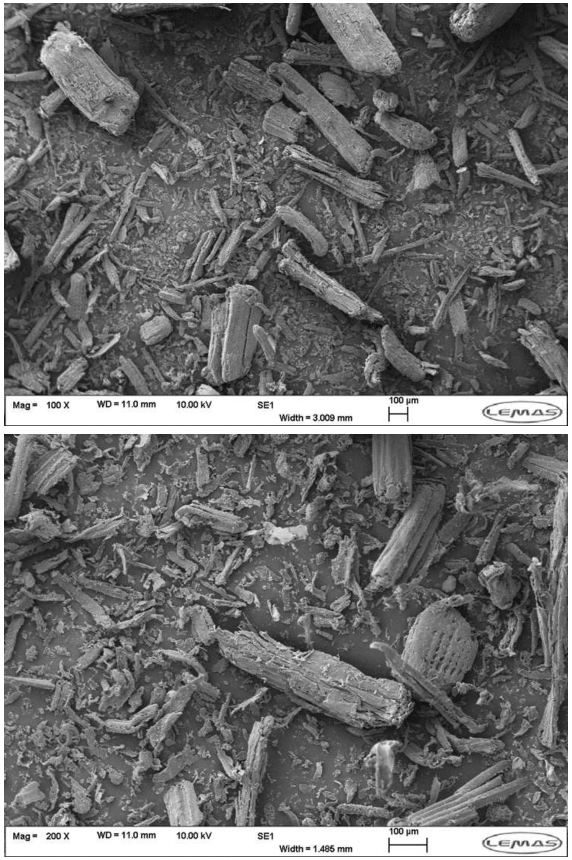
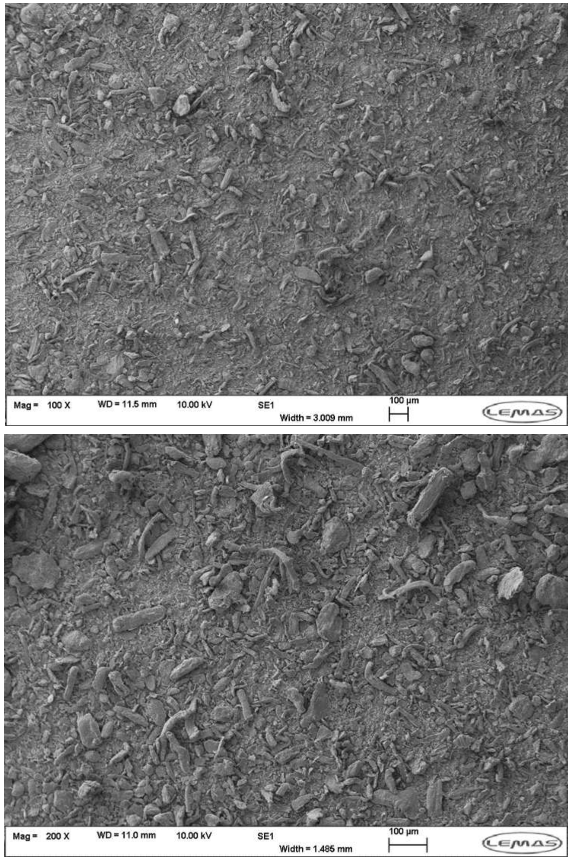
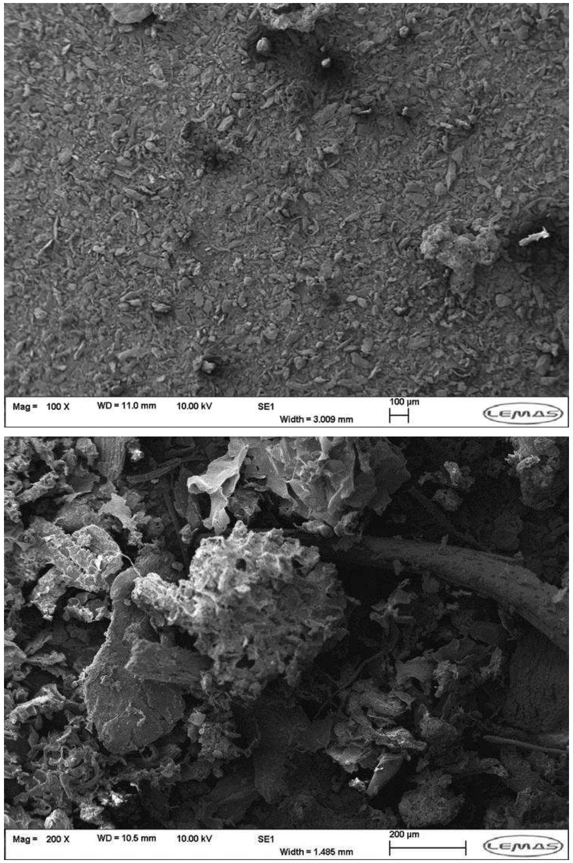
Raw pine wood (YPW)



Steam exploded wood (BP)



Steam exploded wood (Post explosion)



Chemical characterisation	Steam exploded pine wood (BP)	Post explosion residues of steam exploded pine wood		
		BP<63μm	BP(63-150μm)	BP(150-300μm)
% 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	4.4	4.8	4.7	5.8
% VM (daf.)	78.6	73.9	76.9	76.8
% FC(daf.)	21.4	26.1	23.1	23.2
% Ash	2.7	8.2	7.02	6.1
CV (MJ/kg) daf	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

The residue analysis shows that the dust that did not burn in the explosions was very similar to the original dust composition.

The ash increased as the ash from the burned biomass was collected in the residue as well as the ash in the unburned particles.

The volatile content was reduced slightly and the fixed carbon increased slightly.

There was little change in the CV of the original steam exploded pine and that of the residue.

Also particle size analysis showed no evidence of preferential burning of the fines. The flame front had an aerodynamically induced separation of the coarse and fines due to the action of the explosion induced wind. However, this did not affect the movement of the bulk mass of dust ahead of the flame that accumulated on the wall ahead of the flame impingement and extinction at the wall.

Contents

1. Introduction
2. Fire and Explosion Hazards Associated in the Handling of Pulverised Biomass Dusts
3. Characterisation of Biomass in Comparison to Coals
4. Modified 1m^3 explosion vessel with new calibrated disperser for coarse dust testing
5. Minimum Explosive Concentration in terms of Burnt Equivalence Ratio
6. Measurements of Explosibility Characteristics e.g.
   6.1 Deflagration Index (K_{st})
   6.2 Maximum Explosion Pressure (P_m/P_i)
   6.3 Turbulent Flame speed (s_{ft}) and Laminar Burning Velocity (u_L)
7. Post Explosion Analysis and Proposed Model for Coarse Particles Gasification
8. Conclusions

Conclusions

- Steam exploded pine was an explosion hazard but was significantly different to other biomass for the same particle size distribution.
- The MEC of different size fractions were determined to be in the range of $0.29\text{-}2.2\O_{\text{burnt}}$ with the lower MEC for the finer fraction (<63µm) and higher values for coarse size fractions.
- Normalised peak explosion pressure of the steam exploded pine wood samples was measured to be 8.6 bar for finer size fraction and no smaller than 7 bar for coarse size range fraction containing minimum fines (150-300µm).
- The deflagration index (43-122 bar m/s) and turbulent flame speed (1.4-5.4 m/s) were low and comparable to other biomass.
- A Flame propagation model was proposed for preferential burning of fine particles with coarse sized particles lagging the flame front and gasifying in the burnt gases. The fine fraction was only a small fraction of the coarse dusts and so a high concentration of the coarse dust was required to give a flammable fine fraction Ø.