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Title: Explosion characteristics of pulverised torrefied and raw Norway spruce (*picea abies*) and Southern pine (*pinus palustris*) in comparison to bituminous coal

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ABSTRACT

Pre-treatments, such as torrefaction, can improve biomass fuels properties. Dedicated and coal co-firing plants, in which pulverised biomass and torrefied biomass can be used, are exposed to explosion hazards during handling, storage and transport from the mills to the boiler. Data on the explosion characteristics of biomass and torrefied biomass are scarce. This study presents explosion characteristics (maximum explosion pressure, deflagration index and minimum explosible concentration) of two torrefied wood samples and compares their reactivity to that of their corresponding untreated biomass materials and to a sample of Kellingley coal. Torrefied biomass samples showed higher reactivity, overpressures were around 9 bar (0.9 MPa, 1bar= 10^5 Pa) for all biomass samples irrespective of size or sample composition. Derived laminar burning velocities ranged between 0.1-0.12 m s⁻¹, and were much higher than that of coal (0.04 m s⁻¹). These differences influence the design of explosion protection measures and can be used to introduce suitable modifications for safe operations with torrefied biomass.

Keywords: biomass, torrefaction, dust, explosion, *picea abies*, *pinus palustris*

1. INTRODUCTION

As a result of higher volatile, oxygen and hydrogen content, biomass begins to burn at lower temperatures and at a faster rate than coal. The higher moisture content tends to result in different storage requirements whilst the biomass poor grindability, low bulk density and generally fibrous non-spherical particle shape results in different transport requirements (pre and post grinding) to those for coal (1).

Torrefaction is a thermal pre-treatment process applied to biomass fuels in order to improve some of the aforementioned properties. During the process, biomass is subjected to temperatures of 200 °C-300 °C in an inert atmosphere for an optimised period of time; some moisture and volatiles are driven off and the main components of biomass (cellulose, hemicellulose and lignin) partially decompose to different pyrolysis products, depending on the torrefaction temperature and residence time (2). The end target fuel is similar to low rank coals (hydrophobic, more brittle and more energy dense than the parent material), and therefore it is an attractive product with lower transportation and retrofitting costs. Research into torrefaction has been intensified over the last few years (2-8), however technologies are still not sufficiently scalable and there are a few techno-economical barriers to overcome in order to obtain a homogeneous and viable product for the power generation industry. There is an increasing interest in non-pulverised torrefied fuels for domestic heating as well and it appears that such smaller scale application is the most viable short term option for torrefaction, while the technology develops (9).

The preferred method for generation of power from biomass fuels is through combustion, most likely with pulverised fuels. Fine powders can also be created when handling these fuels, during pelletising, or unloading (10, 11). Powders can pose an explosion hazard and the ATEX and DSEAR regulations (12, 13) are in place to reduce the risk of loss of property and personnel due to hazardous materials.

However, the number of fire and explosion incidents involving dry biomass materials is increasing. More than a dozen incidents were reported in the first trimester of 2014, including pellet manufacturing plants, power plants, storage silos, etc. This indicates inadequacy of the safety systems and procedures and lack of data and knowledge about the explosibility of biomass materials (11). The

reason behind the lack of data is that the standard technique for the explosion characterisation of dusts is inadequate due to the biomass characteristics. The standard method for the explosion characterisation of a powder uses the ISO 1 m³ vessel which consists of a 1 m³ explosion chamber attached to a 5 L dust holder where dust is initially placed. This holder is pressurised to 20 bar allowing dust to flow into the explosion chamber through a 19 mm delivery pipe where the dust cloud is ignited. The low bulk density of biomass impedes testing high dust loadings where the most reactive mixtures usually occur; additionally the fibrous nature of some biomass products results in poor ability to flow through the dust dispersion system, creating blockages or delivering less powder than intended. In order to overcome these issues the dust holder volume needs to be increased and the delivery system modified in such way that the turbulence levels inside the vessel match those of the standard system. The Leeds group has calibrated a new delivery system (14) and a higher volume dust holder (10 L) that can be used to characterise the explosibility of fibrous biomass (15), which has enabled the authors to obtain the first available data in the literature for torrefied biomass.

Other authors have also found the same challenges regarding the method for explosion characterisation with fibrous dusts (16), and conceived different systems in order to overcome the delivery and dust holder challenges, however results showed a big variance and suggested that turbulence levels inside the vessel could be dissimilar.

Explosion characteristics of non fibrous biomass powders have been investigated by other researchers and by the Leeds group, where the residues found after explosion have been analysed (17-20). Other studies on the explosibility of fibrous biomass are available (21), but these used the Hartmann tube method which was criticised due to poor dispersion of the dust and abandoned in favour of the current standard methods using the 1 m³ and 20 L sphere vessels. Table 1 shows a summary of explosion characteristics found in the more recent literature for biomass. No results for torrefied biomass could be found in the open literature.

Table 1: Literature explosion characteristics of various biomass fuels

Fuel	K_{st} (barms ⁻¹)	P_{max} (bar)	MEC (gm ⁻³)	Reference
Cork	179	7.2	40	[17]
Walnut shells dust	105	9.4	70	
Pine nut shells dust	61	8.9	-	[16]
Pistachio shells dust	82	9.3	90	
Wood	115	8.6	30	
Bark	132	9.0	30	
Forest residue	87	8.6	60	
Spanish pine	44	7.7	90	[15]
Barley straw	72	7.9	90	
Miscanthus	53	7.8	120	
Sorghum	41	7.3	120	
Rape seed straw	23	6.7	210	
Wood dust (beech and oak mix)	136	7.7	-	[21]
Forest residue (bark and wood)	92	9.1	20	[22]
Wood dust, chipboard	102	8.7	60	[23]
British Columbia wood pellets	146	8.1	70	
Nova Scotia wood pellets	162	8.4	70	
Southern yellow pine wood pellets (USA)	98	7.7	25	[24]

According to the literature, biomass dusts are St-1 dusts (moderately explosible) with maximum pressures around 7-10 bar. Minimum explosible concentrations range from as low as 30 g m⁻³ to 210 g m⁻³. These characteristics strongly depend on particle size, moisture content or dust composition.

The objective of the present study was to assess the effect of torrefaction on the reactivity of biomass by comparing the explosion characteristics of torrefied fuels with that of the corresponding biomass material prior to torrefaction and also to Kellingley coal. Properties such as particle size, moisture content or surface area have also been monitored before and after explosions to understand how reactivity changes due to dust properties and how particles burn during an explosion. Fundamental combustion properties such as turbulent flame speeds and burning velocities have also been derived and can be used for the design of burners and safety systems and for modelling purposes.

2. EXPERIMENTAL METHODOLOGY

2.1. Fuels and sample preparation

Two pre-treated (torrefied) biomass and their corresponding untreated biomass materials were used in the present study. Southern pine harvested in Mississippi and Norway spruce from Sweden and the corresponding torrefied samples were supplied by New Biomass Energy LLC and Sea2Sky Energy

UK Ltd respectively. Substrates were of unknown provenance and the chain of custody is not known. The species and the cultivars cannot be specified, nor can the specific process conditions in the preparation of the torrefied samples, and while the authors BELIEVE that this work exemplifies the difference between samples and processes - there is a reasonable concern that there may be substrate factors that influence the results obtained. Full characterisation was therefore performed for all samples and is provided in section 3. Torrefied biomass samples were supplied in quantities of around 20 kg whereas smaller quantities of raw samples were available (ca. 5 kg). Due to this, raw biomass materials were not available for full explosion characterisation and could only be used to establish a trend for comparison. All samples were supplied in chips or pellets. Following the standards requirement to characterise the explosibility of dusts with powders not exceeding 63 μm (26), samples were pulverized in stages using a Retsch Cutting Mill SM100 to <500 μm and a Retsch Ultra Centrifugal Grinding Mill ZM200 using a 60 μm sieve. All samples were stored in sealed containers.

Residues found inside the explosion chamber after explosion tests were collected using a Numatic MFQ-372 vacuum cleaner fitted with NVM-1CH dust bags and kept in closed sample bottles. Although residues of all explosions were collected and quantified, which allowed for corrections to be applied to the concentration, only the residue from the most reactive concentration was characterised. The weight of dust collected from the dust holder remained undispersed and did not participate in the combustion reaction. Its weight could be subtracted to the initial weight placed in the dust holder to express the concentration as the “injected concentration” rather than the nominal concentration, according to the following equation:

$$\begin{aligned}
 & \text{Injected concentration}(g\ m^{-3}) \\
 & = \frac{\text{Mass into dust holder}(g) - \text{Dust holder residue mass}(g)}{\text{Vessel volume}(m^3)} \quad (1)
 \end{aligned}$$

2.2. Fuel characterisation

All fuels, before and after explosion were analysed for their composition through elemental and TGA-proximate analysis using a Flash 2000 Thermoscientific C/H/N/S analyser (oxygen content was

calculated by subtraction), and a TGA-50 Shimadzu analyser respectively. The elemental composition was used to derive the stoichiometric fuel to air ratio according to the method described in (27). In addition, in order to compare fuels with different composition, the concentration of dust clouds was expressed as an equivalence ratio (ratio of actual to stoichiometric concentrations). The gross calorific value (GCV) of all samples was determined in a Parr 6200 bomb calorimeter to the specifications of BS ISO 1928:2009 (28). Bulk densities of all pulverized fuels were determined weighing increasing amounts of fuels in a known volume. The results were expressed as the average of 10 measurements. Furthermore, the density of particles (true density) was measured using an AccuPyc 1330 Pycnometer.

The morphology of particles before and after explosion was assessed through Scanning Electron Microscopy (SEM) images of sputtered gold coated samples using a Carl Zeiss EVO MA15 instrument and the particle size distributions were determined using a Malvern Mastersizer 2000 instrument.

The surface area and porosity of fuels were also determined through Brunauer–Emmett–Teller (BET) analysis in a Micrometrics Tristar 3000 analyser.

2.3. Explosion characterisation: ISO 1 m³ vessel

The ISO 1 m³ vessel was modified and calibrated to be used with fibrous biomass materials. Further details are presented elsewhere (14, 15, 29). The set-up consisted of a 1 m³ volume explosion chamber connected through a 19 mm internal diameter pipe to an external 10 L dust holder (Fig.1).



Figure 1: Leeds ISO 1 m³ vessel

Initially the dust sample was loaded into the external dust holder and pressurized to 10 bar. A fast acting valve separated both the dust holder and explosion chamber. On activation of the valve the dust was pushed through the delivery system and dispersed inside the explosion chamber through the especially design perforated wall-mounted, spherical nozzle (Fig.2). After a calibrated delay of 500 ms after the start of dust dispersion into the vessel, ignition of the dust took place by means of two 5 kJ chemical igniters placed in the geometric center of the explosion chamber, firing into a perforated hemispherical cup to ensure central ignition and spherical propagation, as far as possible.

Prior to dispersion of the dust from the dust holder, the explosion chamber was evacuated so that on addition of the dust from the dust holder, the initial pressure at the time of ignition was 1.013 bar.



Figure 2: Spherical nozzle injector

After an explosion in the 1 m³ vessel, dust residues were found both in the dust holder (not dispersed) and in the explosion chamber. The dust found in the dust holder did not participate in the combustion reaction and therefore it was accounted for to correct the amount of dust present inside the explosion chamber (injected concentration). However, the dust that remained in the explosion chamber was a mixture of burnt, partially burnt and unburnt material. This residue was analysed in order to understand the combustion mechanism during the explosion.

The vessel was fitted with Keller PA11 piezoresistive pressure transducers for recording of pressure-time histories and also with arrays of exposed junction type-K thermocouples in the horizontal (left and right) and vertical (downwards) directions. These thermocouples allowed determination of times of flame arrival to each thermocouple position and derivation of flame speeds in all directions. The overall radial turbulent flame speed $(S_F)_T$ for a given test was the average of the flame speed in each direction.

K_{st} was computed from the maximum rate of pressure rise obtained by combustion in the 1 m³ volume closed vessel according to:

$$K_{st} = \left(\frac{dP}{dt} \right)_{max} \cdot (V^{1/3}) \quad (2)$$

The maximum pressure and the maximum rate of pressure rise for a given mixture were derived from the pressure-time histories (Fig.3). The maximum pressure for a given mixture of dust was normalised for the initial pressure at the time of ignition (P_i).

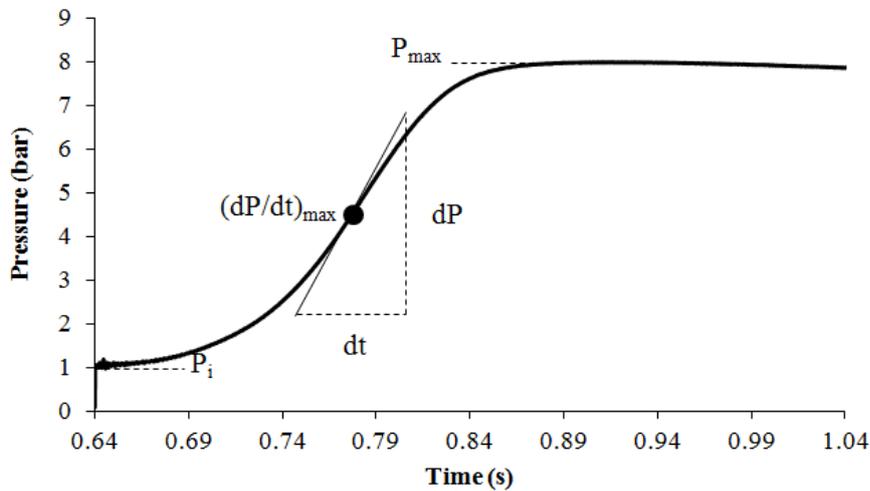


Figure 3: Pressure-time history and derivation of K_{st} and P_{max} for 500 g m^{-3} of torrefied Norway spruce

K_{st} and P_{max} for a particular dust are usually determined as a function of concentration, as shown in Fig.4, and the maximum values over the investigated range are used in the design of safety systems (as they represent the worst case scenario).

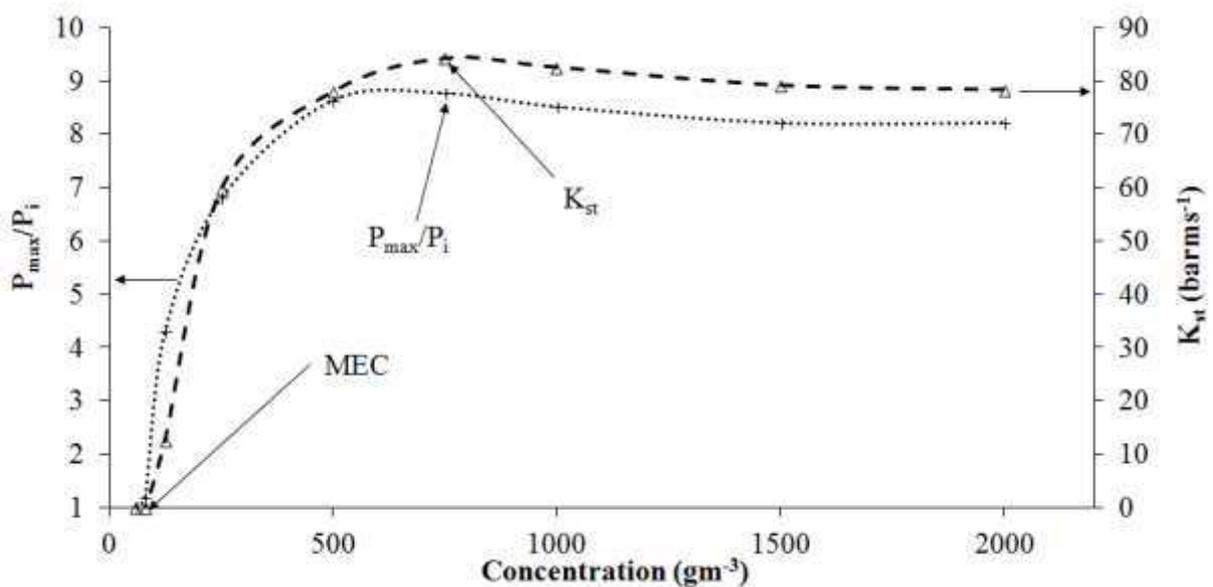


Figure 4: Explosion characteristics of Pine wood mixture

In dust explosions the maximum rate of pressure rise and the maximum explosion pressure can be found at different dust concentrations. Unlike dusts, flammable gases have a narrow flammable range and both the pressure and the deflagration index decrease at rich mixtures until a mixture of gas and air is found for which a flame cannot propagate. However, for dusts there is a limitation on the testing methods that prevents the determination of the rich flammability limits. In the specific case shown in Fig.4, it was possible to test a nominal concentration of 2000 g m^{-3} which corresponds to a mixture 11 times richer than the stoichiometric. Very few researchers have reported measurements of the upper flammability limits: Deguingant et al.(30) measured the upper flammability limit for a coal dust at a mixture 30 times richer than stoichiometric. If a similar upper flammability limit was assumed for a biomass with a bulk density of around $\rho=200 \text{ kg m}^{-3}$ then a dust dispersion volume larger than 30 L would be needed. It is common practice to run mills at very high concentrations to avoid explosions (1), however there is no evidence at present that the same practice is safe for biomass fuels.

Fundamental combustion properties such as turbulent flame speeds and burning velocity could be measured and derived from the tests. All of those parameters can be used for the design of safety systems and for modeling of explosions but also for burner design.

Turbulent flame speeds $(S_F)_T$ and turbulent burning velocities, S_T , are related as follows,

$$(S_F)_T = E_p \cdot S_T \quad (3)$$

where E_p is the adiabatic expansion ratio at constant pressure. The relationship between laminar (S_L) and turbulent burning velocities is given by the following equation,

$$S_T = \beta \cdot S_L \quad (4)$$

where β is the turbulence factor of the vessel. β was found to be 4.03 for the Leeds 1 m^3 ISO vessel by performing laminar and turbulent gas explosions by adding pressurized air from the dust pot, which provided an analogous turbulence to that present in dust explosions. Therefore combining the

previous equations, it was possible to calculate the laminar burning velocity from the measured turbulent flame speeds using the following relationship (31):

$$S_L = \frac{(S_F)_T}{E_p \cdot \beta} \quad (5)$$

This method has proved to give comparable laminar burning velocity results to those available for gases in the literature (31).

The calibrated, modified 1 m³ system allows testing fibrous biomass and torrefied biomass of <60 μm. However, for samples containing bigger particles, at high dust loadings, the system becomes inadequate as increasing mass of dust remained undelivered in the dust holder. Although the system allows determining the “legal” values for K_{st} and P_{max} using samples of <60 μm, this particle size is uncharacteristic of the powders actually handled in the industry. Coal mean particle size encountered in power generation is typically around 20 μm as opposed to biomass particles which can reach the order of a few millimeters long. For successful testing of such powders it would be desirable to design a dispersion system where the dust is placed directly inside the vessel. The Leeds group is currently working on such design.

3. RESULTS AND DISCUSSION

3.1. Fuel characterisation

All fuels characteristics are summarized in Table 2. The composition of the biomass and torrefied biomass samples is similar to typical values in the literature (32, 33).

Table 2: Fuel characterization

	Norway Spruce	Torrefied Norway spruce	Southern pine	Torrefied Southern pine	Kellingley Coal
Elemental Composition (wt%, as received)					
Carbon	48.1	54.8	48.4	54.0	65.0
Hydrogen	5.6	5.2	5.4	5.2	4.1
Oxygen	36.3	30.7	38.1	32.5	5.5

Nitrogen	0.0	0.7	0.6	0.7	2.4
Sulfur	0.0	0.0	0.0	0.0	2.2
TGA-Proximate (wt%, as received)					
Moisture	5.8	2.7	5.0	3.3	1.7
Volatile Matter	79.0	69.4	78.5	70.3	29.2
Ash	4.1	5.8	2.5	4.3	19.1
Fixed Carbon	11.1	22.1	14.0	22.1	50.0
Stoich. Concentration	184	163	193	168	111
GCV (MJ/kg)	19.2	20.6	19.4	21.6	27.2
Bulk Density (kgm ⁻³)	175.6	236.2	268.4	415.4	443.0
True Density (gcm ⁻³)	1.55	1.49	1.49	1.45	1.48
Energy density (GJm ⁻³)	3.4	4.9	5.2	9.0	12.0
Particle Size D ₅₀ (μm)	148.5	38.5	53.2	36.6	25.51
Surface area (m ² g ⁻¹)	0.65	2.10	1.71	1.47	3.69

Results show the effect of mild pyrolysis (torrefaction) on the elemental and proximate composition, where carbon and fixed carbon contents are increased and hydrogen, oxygen, volatiles and moisture contents are decreased. In comparison to Kellingley coal, biomass and torrefied biomass samples have lower energy density, although the energy density improves significantly after torrefaction increasing by 44% and 73% for Norway spruce and Southern pine respectively. Biomass and torrefied biomass samples have more than twice as much volatile matter as coal. Torrefied biomass samples and coal contained larger fraction of fine particles. Surface area is variable for all samples, although it is higher for the coal sample. Bulk density is increased during torrefaction; in the case of torrefied Southern pine is almost as high as for Kellingley coal.

3.2. Explosion characterisation.

Figures 5 and 6, show the reactivity plots for the torrefied samples and their raw biomass counterparts in terms of K_{st} and maximum explosion pressure for a range of concentrations within the flammable range.

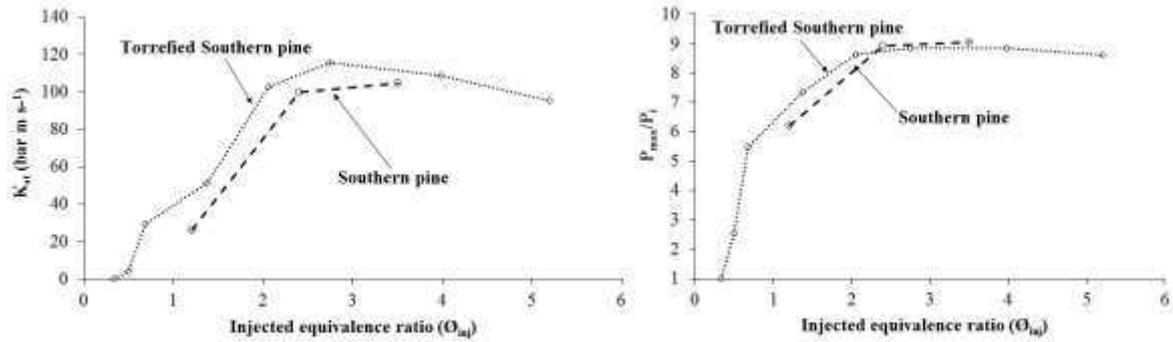


Figure 5: K_{st} (left) and P_{max}/P_i (right) as a function of dust equivalence ratio for torrefied and raw Southern pine

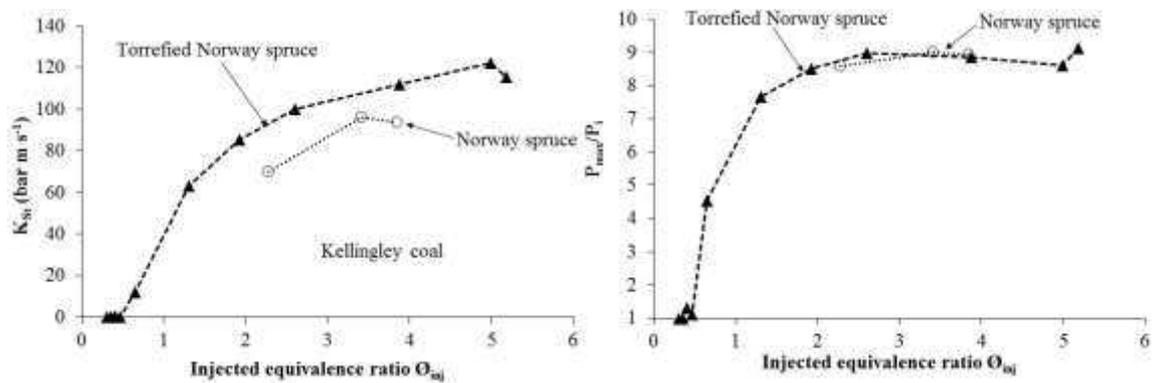


Figure 6: K_{st} (left) and P_{max}/P_i (right) as a function of dust equivalence ratio for torrefied and raw Norway spruce

Greater difference is observed in the reactivity in terms of K_{st} , whereas the maximum explosion pressure remains very similar for both torrefied and raw biomass. K_{st} is usually more affected by dust properties that can affect the rate of combustion, such as particle size or surface area, whereas maximum pressure is affected by parameters that can concern flame temperature, such as the chemical composition. Therefore the difference in reactivity between the samples used for the present study must be due to the higher fraction of fines present in the torrefied samples.

It can be observed that the most reactive concentrations are found for very rich mixtures of around $\phi=3$. It should be noted that the calculation of the equivalence ratio is based on the stoichiometry resulting from the chemical composition of the solid sample. In reality the solid sample decomposes

before burning and therefore the combustion stoichiometry should be based on the gas phase pyrolysis products. As these are not available and difficult to determine theoretically or measure experimentally the solid sample stoichiometry is used instead.

An additional consequence of the combustion reaction occurring in the gas phase is that as the combustion reaction did not occur in the surface of the solid, surface area did not have an effect on K_{st} .

The standard requirement for explosion characterisation of dusts is to find a maximum value of K_{st} and two concentrations either side of it with lower reactivity. It can be observed that while K_{st} decreases in every case for richer mixtures than the most reactive concentration, the maximum explosion pressure does not decrease from around 9 bar.

Figure 7 illustrates the difficulty of biomass dusts to flow into the explosion chamber. The percentage of mass left in the dust holder increases as the mass placed in the dust holder increases for all biomass and torrefied biomass samples, however, for Kellingley coal, a fairly constant residue of 2% of the initial mass remained in the dust holder.

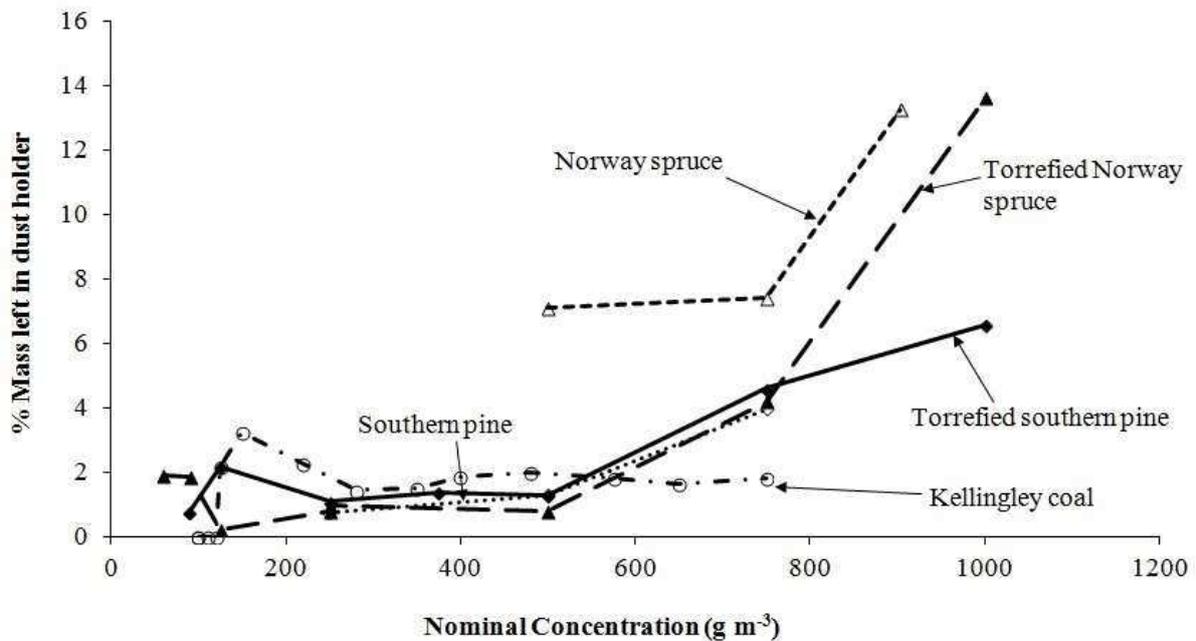


Figure 7: Percentage of initial mass left in dust holder after dispersion

Flame speeds were measured for each mixture tested. Fig.8 shows a plot with thermocouple position against the time of flame arrival to each thermocouple in three directions for a single test with Southern pine. The slope of a linear fit to the points for each direction is the flame speed in each direction. The overall flame speed for a given test is the average flame speed in horizontal right and left and vertical downwards directions. Parallel linear fits to the points in all directions denote spherical propagation. The turbulent flame speed of a given dust is the maximum flame speed found for the flammable range.

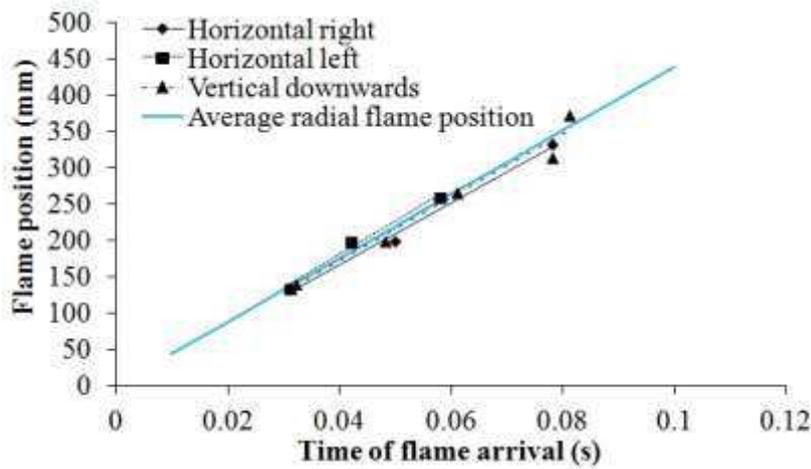


Figure 8: Example of flame speed determination for a single test of Southern pine

Equivalent graphs were built for every test. Fig.9 shows the relationship between K_{st} and the average turbulent flame speed, although there is not enough data to derive an accurate correlation the relationship is linear, therefore either or both parameters can be used as a measure of reactivity.

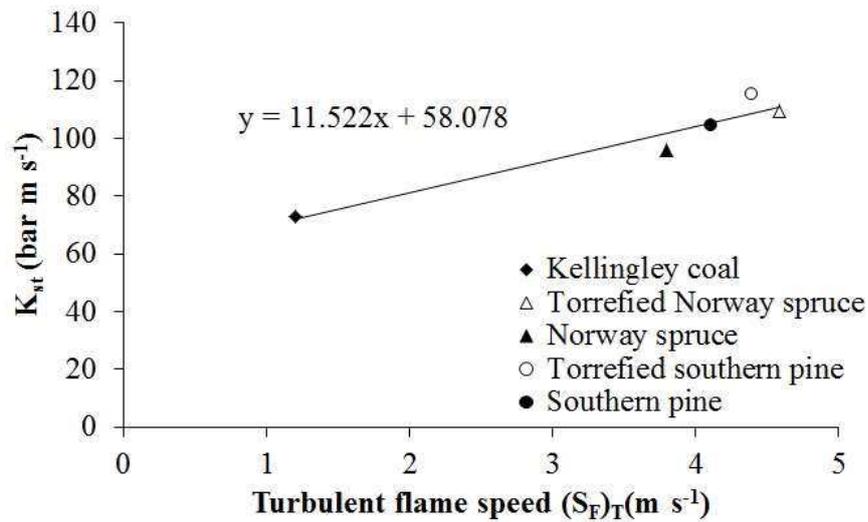


Figure 9: Relationship between maximum deflagration index and turbulent flame speed

Table 3 summarises the explosion and combustion properties measured for all the samples. All biomass and torrefied biomass samples tested are St-1 dusts, as well as Kellingley coal. However the K_{st} for biomass samples are between 30% and 50% higher, which affects design parameters such as the area of a vent needed to protect an enclosure from an explosion. Maximum explosion pressures were found around 9 bar for all biomass samples irrespective of their composition or whether it was torrefied or not which suggests that size properties are the cause of the difference in K_{st} rather than composition. Laminar burning velocities ranged between 0.1 ms^{-1} and 0.12 ms^{-1} for biomass samples. In comparison with Kellingley coal all biomass and torrefied biomass showed higher reactivity. Also less dust was needed for biomass to support flame propagation. Typically, for hydrocarbon gases and dusts, the MEC is found for mixtures of $\phi=0.5$, results found in this work with the 1 m^3 show that torrefied biomass burnt at leaner mixtures than coal. However, residue consisting on burnt, partially burnt and unburnt particles is found in the vessel after the explosion even in lean tests, making accurate quantification of MEC difficult. The authors have developed a new technique using a modified Hartmann technique that can measure MEC (27).

Table 3: Explosion and combustion properties

Fuel	K_{st} (bars s^{-1})	P_{max}/P_i	$(S_F)_T$ (ms $^{-1}$)	S_L (ms $^{-1}$)	MEC (gm $^{-3}$)	\emptyset_{MEC}
Norway spruce	96	9.0	3.8	0.1	-	-
Torrefied Norway spruce	110	9.1	4.6	0.12	54	0.33
Southern pine	105	9.0	4.5	0.12	-	-
Torrefied Southern pine	115	8.8	4.4	0.12	55	0.33
Kellingley coal	73	7.7	1.2	0.04	91	0.82

3.3. Residue analysis

Residues collected from the explosion chamber for the most reactive concentration were analysed.

The results for elemental and proximate analysis are summarized in Table 4.

Table 4: Elemental and proximate analysis of samples before and after explosion

	Norway spruce	Torrefied Norway spruce	Southern pine	Torrefied Southern pine	Kellingley Coal
BEFORE EXPLOSION (wt%, as received)					
Carbon	48.1	54.8	48.4	54.0	65.0
Hydrogen	5.6	5.2	5.4	5.2	4.1
Oxygen	36.3	30.7	38.1	32.5	5.5
Nitrogen	0.0	0.7	0.6	0.7	2.4
Sulfur	0.0	0.0	0.0	0.0	2.2
Moisture	5.8	2.7	5.0	3.3	1.7
VM	79.0	69.4	78.5	70.3	29.2
Ash	4.1	5.8	2.5	4.3	19.1
Fixed Carbon	11.1	22.1	14.0	22.1	50.0
AFTER EXPLOSION (wt%, as received)					
Carbon	48.4	60.6	50.9	58.3	64.3
Hydrogen	5.4	4.1	5.4	4.9	3.5
Oxygen	26.6	21.7	36.5	24.0	7.1
Nitrogen	0.0	1.2	0.6	1.3	1.4
Sulfur	0.0	0.0	0.0	0.0	2.2
Moisture	3.1	2.9	3.7	2.4	1.6
VM	66.5	48.8	72.9	54.8	25.0
Ash	16.6	9.5	2.9	8.9	19.9
Fixed Carbon	13.8	38.8	20.5	33.8	53.5

In regards to the elemental composition the major change occurred in the oxygen content. The residue found after explosion contained less oxygen for the biomass samples, whereas it increased slightly for

coal. The increase for coal was 29%, whereas both torrefied samples saw a decrease of oxygen content of 29% and 26%. Oxygen in coal is present in very stable bonds, nitrogen and hydrogen contents in the residue were reduced which resulted in the relative increase of oxygen content. On the other hand oxygen in biomass forms fragile bonds and therefore oxygen will be readily released during devolatilisation. Changes in other elements were small and similar to the experimental variability of the instrument.

The volatile matter content in the residue decreased in all cases. The thermogravimetric analysis of the samples showed that biomass and torrefied biomass samples lost most of their volatiles at a temperature where Kellingley coal had only started devolatilising (Fig.10). Therefore it would have been expected that the post explosion residues of biomass and torrefied biomass samples would show very high devolatilisation.

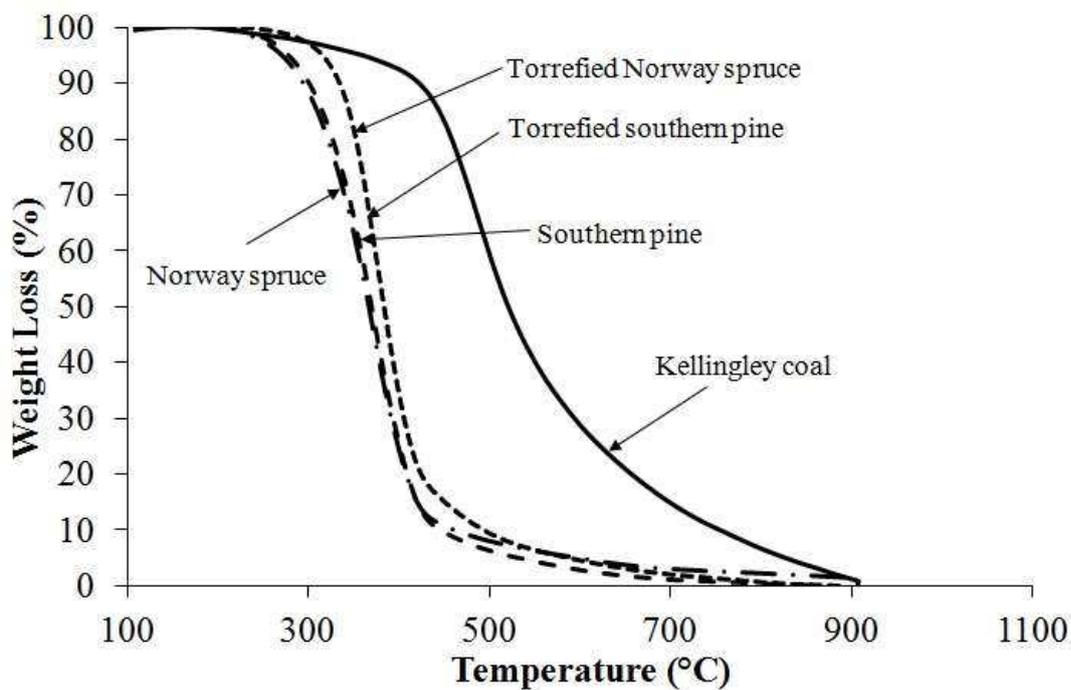


Figure 10: TGA normalised for volatile weight lost

However, the residue of raw biomass samples was found to contain only between 7% and 16% less volatiles than the original sample. Similarly, coal lost 14% of its volatiles, whereas for both the torrefied samples the residue contained between 20% and 30% less volatiles. It should be noted that

heating rates in an explosion are much faster than the heating rates using in a thermogravimetric analysis and studies in the literature for fast pyrolysis of coal have found that rapid heating affects the amount of volatiles produced even above the proximate volatile matter (34, 35). In the case of biomass this has also been found as well as little or no char formation (36-40).

There is a slight increase of the ash content in the residue which is more prominent for Norway spruce. The fixed carbon content in the residues also increased in every case. The increase was significantly smaller for coal, and noticeably higher for the torrefied samples. In view of these results it could be concluded that the dust found in the explosion chamber after an explosion had been slightly pyrolysed. Loss of volatiles and increase in fixed carbon and ash are typical characteristics of high temperatures in the absence of air (as it occurs during torrefaction, but inside the explosion chamber, at higher temperatures and heating rates).

Evidence presented elsewhere (20) suggests that the bulk of the residue had not taken part in the explosion but was instead thrown against the vessel wall where only the top layer was partially pyrolysed and the rest remained unreacted. This detail is masked in the bulk residue analysis carried out here, as opposed to the layer analysis in (20). An evaluation of the morphology of particles before and after explosion (Fig. 11) using SEM images shows that for the raw Southern pine sample the structure of most particles remained similar to the original sample before explosion. However, occasionally char structures could be found. Conversely, the residue of torrefied Southern pine after explosion test presented predominantly char structures mixed with unaffected wood. This behavior was similar to that of coal, where also the presence of char structures prevailed in the mixture with original particles.

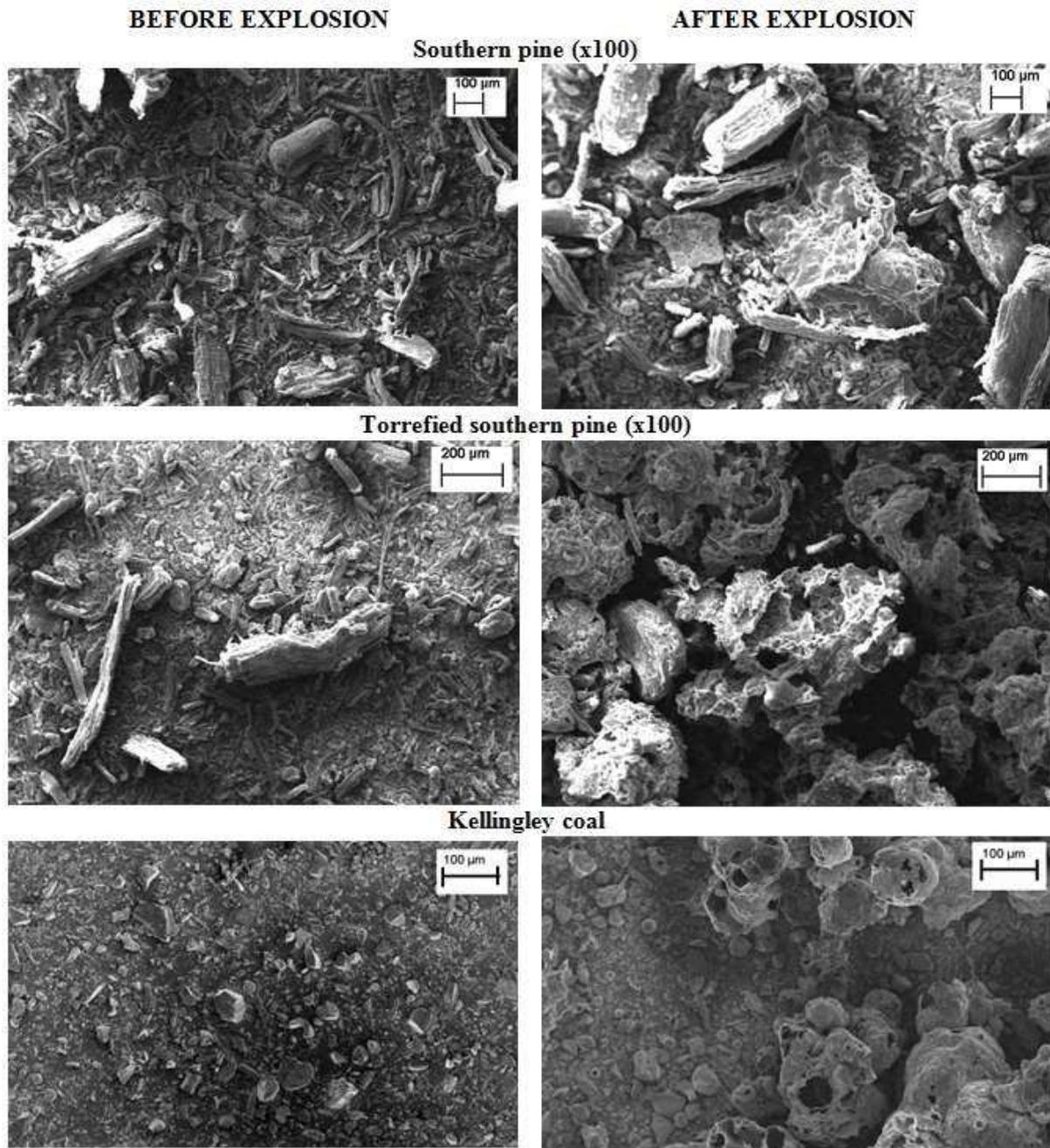


Figure 11: SEM images of raw Southern pine, torrefied Southern pine and Kellingley coal

The same behavior as for Southern pine (raw and torrefied) was found for raw and torrefied Norway spruce. The char structures showed hollow structures with signs of devolatilisation such as blow out holes; in addition, these structures appeared to fuse together forming clusters of bigger overall size than the original particles.

The particle size distribution of both residues and original samples is compared in Figures 12 to 14. For both raw Norway spruce and Southern pine samples the particle size distribution of the residue was virtually the same as for the original sample. On the other hand, residues from explosions with torrefied samples and Kellingley coal showed a noticeable difference in the particle size distribution where the residue presents bigger particles. This could be a reflection of the presence of char particles fusing together, forming big clusters.

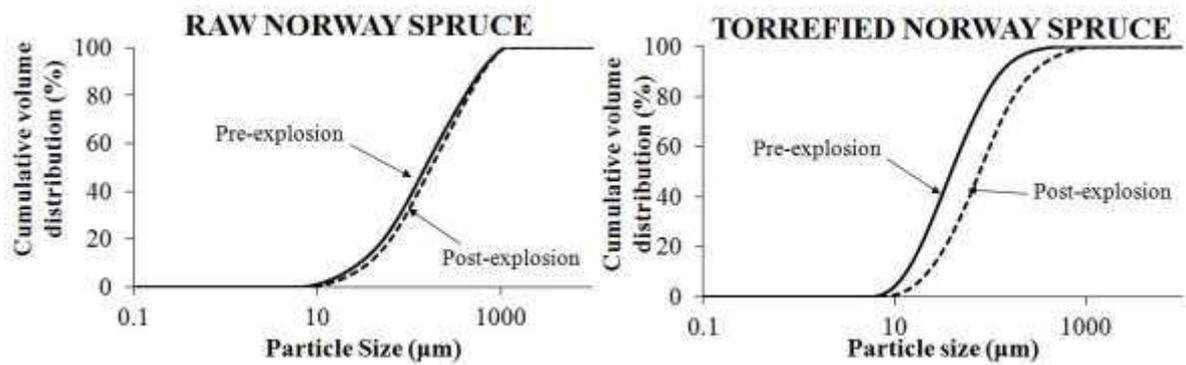


Figure 12: Particle size distribution of raw (left) and torrefied (right) Norway spruce before and after explosion

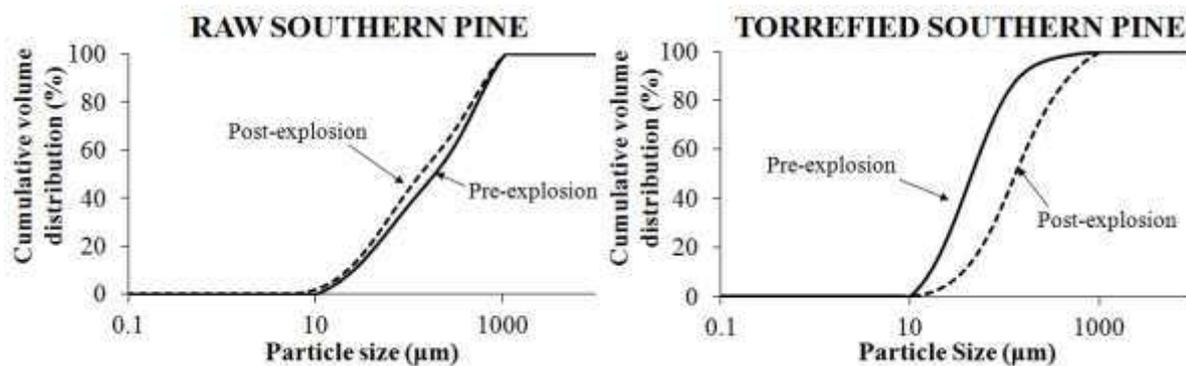


Figure 13: Particle size distribution of raw (left) and Torrefied (right) Southern pine before and after explosion

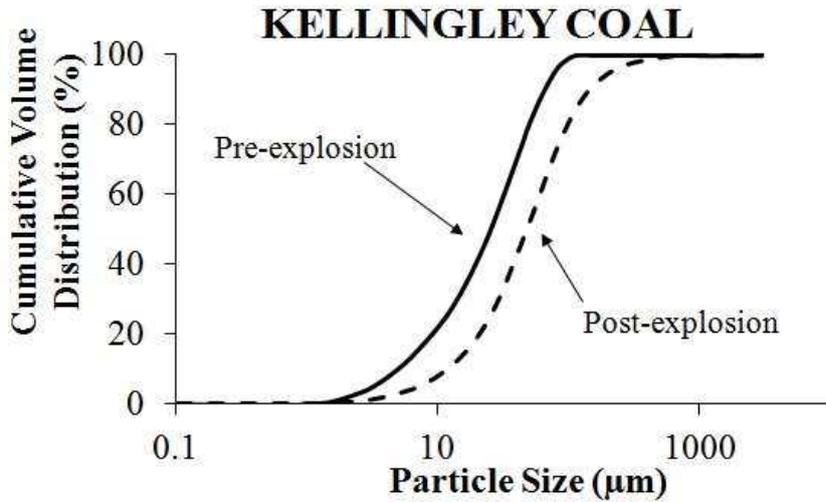


Figure 14: Particle size distribution of Kellingley coal before and after explosion

The particle density was also assessed for residues and original samples, the results are summarized in Table 5. It can again be noted that the particle density changes considerably for torrefied samples and for coal, whereas there is little change in particle density for the raw biomass samples.

Table 5: True density of samples before and after explosion

	TRUE DENSITY (kg/m ³)	
	Pre-explosion	Post-explosion
Norway spruce	1546	1543
Torrefied Norway spruce	1494	1570
Southern pine	1491	1503
Torrefied Southern pine	1454	1503
Kellingley coal	1484	1641

Slatter et al. (20) postulated that when the flame front reaches the wall it impinges over the outer layer of dust, therefore subjecting it to high temperatures. At this time all available oxygen should have been consumed and pyrolysis conditions are met, however complete combustion is not achieved due to lack of oxygen and the loss of heat through the walls. The extent to which samples are affected (in terms of their composition) is greater for biomass and torrefied biomass as according to the thermogravimetric analysis these samples have shown to fully devolatilise when coal has only started losing volatiles.

There are a number of studies in the literature where the fast devolatilisation of coal and biomass has been revised. Di Nola et al. (41) summarized some of these works. It was generally found that volatile yields increased significantly with temperature. Zanzi et al. (42) found that the heating rate affects much more the pyrolysis of biomass than coal. Char formation is promoted when secondary reactions occur between volatiles and char. The lesser formation of char has been previously attributed to the higher cellulose content of biomass. At low temperatures and low heating rate, cellulose dehydrates to anhydrocellulose (which promotes char yields). These reactions are dominant at $<300\text{ }^{\circ}\text{C}$. At high heating rates the time at which the biomass remains in that temperature range is low and there is not enough time for cellulose to dehydrate, which leads to little char formation. Torrefied biomass contains less cellulose as it decomposes during the torrefaction treatment in more or less degree depending on the temperature and residence time, therefore, this could explain the higher presence of char structures in torrefied biomass residues.

4. CONCLUSIONS

The modified and calibrated system for testing fibrous biomass materials in the Leeds ISO 1 m³ vessel permitted conducting the present study on the explosion characteristics (K_{st} , P_{max} , MEC) of two torrefied biomass samples (Norway spruce and Southern pine) and their comparison to the untreated biomass and a standard UK coal (Kellingley coal). The torrefied samples improved grindability allowed for finer particles to be created when pulverised in comparison to their untreated counterparts.

The maximum explosion pressure has been found to be about 9 bar for all biomass samples regardless of being torrefied or raw biomass, their composition or particle size. In comparison to Kellingley coal, biomass samples present higher maximum explosion pressure. All samples were classified as St-1 dusts according to their K_{st} value (weak to moderate explosibility). However, K_{st} values for all biomass samples were higher than that for Kellingley coal. Both torrefied Norway spruce and Southern pine had higher K_{st} than their corresponding raw materials. As K_{st} is typically affected by particle size it is believed that the difference between raw and torrefied biomass is due to the presence of finer particles in the torrefied samples.

Residues collected after the explosion tests were analysed and presented a very similar elemental composition to the pre-explosion sample and the proximate analysis indicated that the residues had undergone only limited devolatilisation. The residues however showed typical signs of having undergone pyrolysis as a result of flame impingement at the walls. An assessment on particle morphology showed that more char structures appeared in coal and torrefied biomass residue samples. These structures fused together forming bigger particles which resulted in particle size distributions with a larger fraction of big particles in comparison to the original samples. Lower formation of char structures was found for raw biomass residue samples; this resulted in particle size distributions for the residues almost identical to the original sample. The low char quantities in the post explosion untreated biomass were attributed to the higher content of cellulose in the raw samples in comparison to torrefied biomass and coal. Further work is underway to corroborate and understand these findings. The explosion reactivity of torrefied biomass was found to be higher than that of coal and therefore suitable modifications should be devised for safety systems where torrefied biomass is used.

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