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Explosion and Flame Propagation Properties of Coarse Wood: Raw and Torrefied

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ABSTRACT

A current production torrefaction process was used and the explosion and flame propagation properties were determined at the particle size of the raw (spruce, pine and fir – SPF) and torrefied biomass. The biomass material as received was sieved to <1mm. Size analysis showed that 10% by mass was <100 μ m and the torrefied sample had 15% <100 μ m. The CV for the torrefied biomass was 10% greater than that for the raw biomass. The ISO 1 m³ dust explosion vessel was used, with a modified and calibrated biomass dispersion system that could cope with very coarse particles. The explosions did not burn all the dust that was present at the start of the explosion and the residual unburnt dust was shown to be the original dust. The equivalence ratio, ϕ , of the propagating flame was based on the burnt dust concentration, ϕ_{burnt} . Raw and torrefied samples were found to have minimum explosion concentrations, MEC, of $2.3\phi_{\text{burnt}}$ and $1.4\phi_{\text{burnt}}$ respectively and this shows that the torrefied sample was more reactive as it had a leaner MEC. The deflagration index, K_{st} , was higher for the torrefied SPF with a peak at 35 bar m/s compared with 24 for the raw biomass. The peak turbulent flame speeds were similar for torrefied and raw biomass at about 1 m/s. The torrefied biomass was more reactive than the raw biomass mainly due to the smaller particles size and 10% higher CV. The mechanism for coarse particle combustion is considered to be due to the explosion induced wind blowing the finer fractions ahead of the flame which burn first with the coarser fractions gasifying in the rich burnt gases behind the initial flame. The rich MEC was caused by the requirement to have the fine fraction above the MEC when only about 10% of the mixture was fine.

KEYWORDS: Flame propagation, torrefaction, biocoal, dust explosions

INTRODUCTION

With the advent of the use of pulverised biomass for electric power generation in coal fired power plants, which accounted for 5.7% of all electricity generated in the UK in 2014, there is a need to know the laminar burning velocity, U_L , of pulverised biomass flames for turbulent burner flame modelling. If the biomass is thermally treated by a torrefaction process to form what is often referred to as a 'biocoal' then this chemically and physically changes the fuel properties and there is no information on the propagation of flames through clouds of pulverised torrefied biomass, apart from that provided by Huescar-Medina et al. [1-5] and Saeed et al. [6]. Thermal pretreatment such as torrefaction results in a more consistent product with a reduced bulk volume that is easier to mill, as fibres of the biomass have been made brittle [7, 8]. Particles of pulverised biomass pose fire/explosibility hazards associated with their handling and there have been a number of fire/explosion incidents in biomass processing plants. One solution is thermal processing and pelletisation using coarse wood as the feedstock so as to avoid grinding the biomass fine enough to become very reactive [9] and this was the principle used in the present work. The immediate purpose of this work was to provide data on the biomass dust explosion risk in a commercial torrefaction plant and in the torrefied product handling. However, the data is also relevant to the

combustion of these fuels in a pulverised flame application, as the size distribution of biomass particles in biomass/coal co-firing or only biomass firing is currently quite coarse in power stations.

For gas and dust flames there is no agreed methodology for burning velocity, S_L measurement and hence no agreed values that can be used in explosion protection design or in pulverised biomass burner design. Andrews and Bradley [10] showed that there were systematic errors in most methods of determining the laminar burning velocity of gases and these were related to the finite thickness of the flame and the assumption of an infinitely thin flame in many of the measurement methods. As the flame thickness of dust flames is greater than gas flames, the measurement problems for U_L for dusts are greater than for gas flames. Some recommended values of burning velocity for gases using measurement methods with low errors were recommended by Andrews and Bradley [10] and adopted by the NFPA in their gas explosion protection standard [11]. For dusts no data base exists for laminar burning velocities, as few measurement methods exist, due to the need for turbulence to keep the dusts in suspension. The lack of a reference standard for the measurement of U_L for gases contrasts with the area of gas flammability limits, where standards do exist [12].

In gas or dust explosion protection using venting or suppression there has always been a legal requirement to take into account, in the vent or suppression design process, the reactivity of the most reactive mixture that the vent is a protection against [13]. In the absence of agreed methods to determine S_L an alternative and less fundamental parameter has been used for many years and this is the deflagration parameter, K . This is determined in a closed spherical vessel explosion by measuring the maximum rate of pressure rise (dP/dt_{max}) times the cube root of the volume, V , $K = dP/dt_{max} V^{1/3}$ (bar m/s). For gases this is usually referred to as K_G and for dusts K_{st} . It should be noted that if the pressure rise is expressed relative to the initial pressure, P_i , then $K/P_i = (dP/P_i)/dt_{max} V^{1/3}$ (m/s) and is thus clearly a rate of flame propagation parameter.

How dP/dt_{max} is measured is detailed in a European Standards for gas [14] and dust [15] explosions. Also required to be measured is the peak explosion pressure and there are standards on how to do this [16]. These reactivity parameters are embedded in the European standards for gas [17] and dust venting [18], but are not used in the wider area of combustion modelling. The measurement procedures for the dust reactivity, K_{st} , requires the ISO standard 1m³ spherical explosion vessel to be used to determine P_{max} and dp/dt_{max} and this is the experimental equipment used in the present work [19].

The standard dust explosion techniques are based on a turbulent dust injection process, as turbulence is required to keep the dust dispersed. The average turbulence can be calibrated by undertaking laminar gas explosions and then operating the air injection system into a premixed gas air mixture to generate the same turbulence as occurs in dust explosions [20, 21] and this method was used in the present work to calibrate the turbulence in the new injection system for coarse fibrous biomass. The reference turbulence factor for the standard ISO injector was determined to be ~4.7 using laminar and turbulent methane/air explosions [20, 21].

For gases K_G is measured in a laminar explosion in a 5L spherical vessel and Bartknecht [22] has published K_G for a wide range of gases in a 5L sphere and these values are quoted in the vent design standards [17]. Up to 2012 the K_G reactivity parameter for gases and Bartknecht's list of values of K_G was part of the gas venting design standards in the USA [23], but have been replaced by a more fundamental gas venting design procedure based on S_L as the reactivity parameter [11]. However, they have not chosen to regulate how S_L is measured, but have specified a reference value for propane, 0.46 m/s, that the measurement method must be corrected to. They also continue to use K_{st} as the reactivity parameter for dust, due to the lack of reliable data for dust U_L . The problem with the K_G approach to gas reactivity is that it is dependent on the vessel volume [24-26], which

is a reflection of the dependence of laminar flame propagation on the distance from the spark [25], due to self-acceleration of the flame caused by the formation of cellular flames. The procedures of Chippett [25] are used to increase U_L due to this effect in the USA gas venting standards [11], but there is no procedure to take this into account in the European gas venting standards [17].

Andrews and Phylaktou [27] showed that for gases the K_G/P_i and U_L gas reactivity parameters are linearly related by Eq. 1. They also showed that for reasonable values of U_L and adiabatic P_m/P_i the predicted values of K_G were in reasonable agreement with experimental K_G measurements.

$$\frac{K_G}{P_i} = 3.16 \left(\frac{P_m}{P_i} - 1 \right) U_L E_p \quad (1)$$

where E_p is the constant pressure expansion ratio which is the unburnt gas to burnt gas density ratio.

For dusts Cashdollar [28] proposed that E_p could be determined as the ratio of peak pressure to initial pressure in a closed vessel dust explosion, as it is quite difficult to calculate E_p for dust, as it is influenced by the water and ash content as well as the elemental composition of the dust. This approach was used in the present work. The key assumption in the derivation of Eq. 1 is that the explosion flame speed is constant across the vessel diameter with no account taken of the rise in pressure, P , and temperature, T , in the later stages of the explosion. The change in U_L with T and P was computed by Bradley and Mitcheson [29] and the results show that the final value of U_L would only be 20% higher than the initial value which is a relatively small error. Kumar [30] has derived an equation similar to Eq. 1 that includes the P and T dependence of U_L but gives similar values to those from Eq. 1. Sattar et al. [21] showed, for the first time experimentally, that K_G and U_L were linearly related as Eq. 1 predicts, but only if both reactivity parameters were measured in the same explosion vessel. Sattar et al. [21] showed that the ISO 1m³ explosion vessel could be used for gas explosions to measure the constant pressure explosion laminar flame speed, U_L , using arrays of exposed junction thermocouples to determine the flame arrival time. The infinitely thin flame front assumption then enables the laminar burning velocity U_L to be determined by Eq. 2.

$$U_L = \frac{S_L}{E_p} \quad (2)$$

Sattar et al. [21] used this approach to determine the maximum burning velocity of methane-air to be 0.42 m/s, which they showed to be in good agreement with a wide range of other measurements using reliable techniques [10]. This approach was adapted in the present work for determining the laminar burning velocity of dust air mixtures [21].

BIOMASS PROPERTIES AND TORREFACTION PROCESS

The raw biomass sample was a proportionate mixture of three woody biomass: Spruce (S), Pine (P) and Fir (F) that is referred to as the SPF sample with R referring to the raw sample and T to the torrefied sample. The torrefied biomass was manufactured in a pilot plant with a 0.5 tonne per day production capacity of torrefied pulverised biomass, which was tested in the present work. This material was normally passed to a pellitizer process and sold into the thermal heating market as 'biocoal'.

The torrefaction process that was used in this work [31] heats biomass by direct contact with hollow hot flat surfaces (trays), which at steady state operated at 303°C on the top surface and 290°C on the bottom surface. The biomass was injected cold into the torrefier and heat was transferred from

the trays by conduction. On the top side of the trays biomass is moved through the reactor by paddles, that are attached to a rotating shaft and this process gives uniform contact of the particles with the hot surface and a uniform torrefaction of each particle. The mean residence time of biomass particles inside the reactor was 7 minutes, which is typical of other torrefaction processes [32]. Biomass moving through the reactor is traveling down the reactor from one tray to another, being slowly torrefied until it reaches the output chute. A gaseous by-product, torgas, is formed during the torrefaction process, which surrounds the biomass and prevents oxidation and this prevents explosion and self-ignition hazards. The torgas is removed from the torrefier, burnt with air and the hot exhaust gases flow through the hollow plates to deliver the heat required by the torrefaction process. Heat is recovered from the plate outlet gases in a countercurrent heat exchanger which preheats the combustion air. This torrefaction process requires no external energy input, apart from during start up.

The raw and torrefied biomass samples were of coarse particle size distribution of < 3 mm that were sieved to < 1 mm for the present work. The sample particle size was analysed by a Malvern Mastersizer. The elemental analysis was used to determine the stoichiometric air to fuel ratio, A/F [27]. TGA analysis was used to determine the volatile, fixed carbon, ash and water content of the biomass [33, 34]. The biomass composition analysis is shown in Table 1, which shows that torrefaction produced an increase of elemental carbon with a reduction in the % oxygen due to torrefaction. The CV on a dry basis was increased as shown in Table 1. Torrefaction also produced a 10% increase in the stoichiometric A/F, due to the reduced oxygen content.

A feature of dust explosions in the ISO 1 m³ equipment is that a large proportion of the injected dust does not burn in the explosion and thus a mixture concentration based on the injected dust mass is not the concentration that the flame propagated through [3, 21, 34]. Analysis of the post explosion residues for the most reactive concentration is shown in Table 1, which shows that they have almost same composition as that of their parent samples [35]. The weight of the residue was deducted from the weight of the original biomass and after correcting for added ash due to burnt mass, used to compute the burnt equivalence ratio, ϕ_{burnt} .

Table 1. Properties of the raw and torrefied SPF samples and the explosion residues

Biomass	C daf. %	H daf %	N daf %	O daf. %	H ₂ O %	VM %	FC %	Ash %	CV dry. MJ/kg	CV Actual MJ/kg	Stoich A/F g/g	Stoich. actual g/m ³
SPFR	50.4	6.9	1.2	41.4	7.8	73.4	16.2	2.6	19.9	17.8	6.4	187
SPFR residue	51.1	6.3	1.2	41.4	6.8	72.2	17.5	3.5	19.8	17.8	6.3	212
SPFT	54.7	6.9	1.1	37.4	4	74.6	18.1	3.2	21.7	20.1	7.05	183
SPFT residue	57.9	6.2	1.4	34.5	4.2	65.2	22.7	7.8	21.3	18.7	7.3	187

Table 2. Size distribution in μm of the raw and torrefied biomass

Biomass	D ₁₀	D ₅₀	D ₉₀	D _{smd} or D _{3,2}	% $< 100\mu\text{m}$
SPFR	91	451	866	184	11
SPFR residue	69	288	747	124	15
SPFT	73	347	785	151	15
SPFT residue	78	343	781	164	15

The particle size distributions are summarised in Table 2 and this shows that torrefaction reduced the particle size by 20% on a D_{10} basis and 18% on an SMD (Surface mean diameter) or equal surface area basis and increased the proportion of fines ($<100\mu\text{m}$). The analysis of the residue after the explosion showed that for the torrefied material it was almost identical to the original dust in terms of the size distribution in Table 2 and the composition in Table 1. The increase in the ash in the residue was due to the ash of the burnt biomass as well as the unburnt biomass. For raw biomass there was a decrease in the particle size in the residue. The origin of this unburnt biomass was first shown by Sattar et al. [21, 35] and Slatter et al. [36] to be caused by the action of the explosion induced wind ahead of the flame front in blowing particles away from the flame and eventually onto the vessel wall, where they fell onto the floor of the vessel at the end of the explosion. While on the wall they acted as an insulating layer that reduced the rate of vessel cooling, as shown by the reduction in the rate of pressure loss [36].

EXPERIMENTAL METHODOLOGY

The ISO 1 m³ vessel, shown in Fig. 1 (b) for the version used in the present work, with the standard “C” ring particle injector, does not work for pulverised coarse woody biomass as the particles are compressed in the delivery tube and do not emerge from the injection holes. This occurs even where the woody biomass is sieved to $<63\mu\text{m}$, as size and SEM analysis of these particles shows that cylinders of diameter $<63\mu\text{m}$ occur with lengths much greater and these block in the “C” ring. Several modifications were investigated, but for particles with sieved sizes $>63\mu\text{m}$, as used in power stations and as occur in pellet store dusts, no externally located dust injection system could be made to work. The principle of externally based dust driven in by compressed air had to be abandoned and the Hartmann method of dust dispersion was used, whereby the dust was placed inside the vessel in a chamber and dispersed with a blast of air. A hemispherical container was placed on the floor of the vessel, as shown in Fig. 1 (a), that was 0.4m diameter with a volume of 17L and could contain 3.5 kg of biomass particles with bulk density of 200 kg/m³. This was dispersed with compressed air from a 10L external volume at 20 bar pressure. The air was fed via a pipe the same size as the “C” ring to the bottom of the hemisphere and injected through a series of holes around and along the tube end, so that the same total hole area as for the “C” ring injector was used. Calibration of the injection system showed that an ignition delay of 0.5s was required to give the same K_{st} for cornflour as the standard ISO 1 m³ design. This method of dispersion of the dust also gave a spherical flame for cornflour.

Two dimensional arrays of thermocouples were placed horizontally and vertically in the vessel for detecting the time of flame arrival. The sets of thermocouples recorded the time of flame arrival that was used to determine the average flame speeds. It was found that the average flame speed was the same showing that the propagation of flame was uniform in two directions and this was taken as proof that a spherical flame had been achieved. These average flame speeds were measured in the constant pressure region in between 0.2 to 0.7m of the vessel [21].

DEFLAGRATION INDEX, K_{st}

K_{st} as a function of ϕ_{burnt} are shown in Fig. 2 for SPFR and SPFT. The peak K_{st} was 24 and 36 bar m/s for raw and torrefied wood mixture respectively. Although the peak K_{st} occurred at a similar ϕ_{burnt} of 3.0 the torrefied SPF had higher K_{st} at all ϕ and was much more reactive for $<\phi_{\text{burnt}}$ of 2.5. No lean mixture flame propagation for either raw or torrefied biomass were found. Thus biomass with coarse particle size, whether raw or torrefied, will only burn if the overall ϕ of the mixture is rich and the highest reactivity, K_{st} , is for rich mixtures. This does not occur for gaseous mixtures and is unique to coarse dusts, particularly biomass dusts.

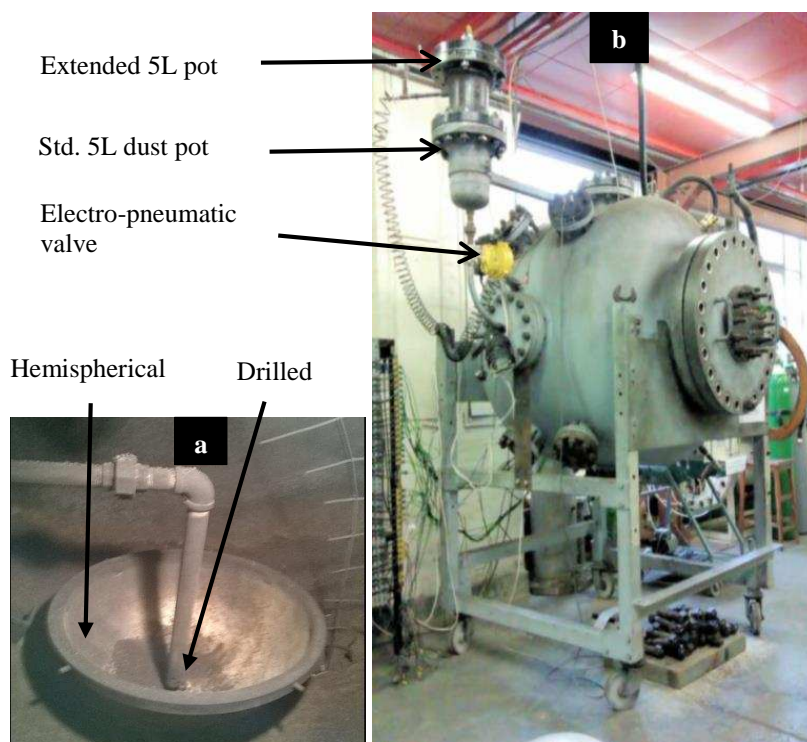


Figure 1. (a) Drilled pipe hemispherical disperser (b) ISO 1 m³ vessel

A mechanism for coarse biomass powders to burn in a propagating flame is proposed to explain these results, which is an extension of that used to explain why about half of the initial dust does not burn in the explosion [21, 34, 36, 37]. The action of the wind, induced by the expanding spherical flame, on particles ahead of the flame with a variable size distribution is to blow the smallest particles close to the gas velocity with the larger particles lagging due to drag effects. The flame front is driven by the finer particles and the larger particles then lag behind and are heated to ignition by the hot burnt gases from the flame front. The mixture has to be very rich for the finer particles ahead of the flame to burn with only <20% of the total mass of particles in the size fraction that will burn easily, as shown in Table 2. A flammable mixture of 20% fine particles with ϕ_{MEC} of 0.4 needs ϕ_{burnt} of at least 2.0 for the overall mixture to burn. This is close to the results in Fig.3 for SPFR. With this model the larger particles are gasified in the rich mixture of the hot burnt gases from the flame burning in the finer fraction. This releases CO [38] and H₂ which has insufficient oxygen to burn, but the volume release keeps the explosion pressure high for rich mixtures.

The maximum explosion pressure, P_m , to the initial pressure, P_i , is shown in Fig. 3 as a function of ϕ_{burnt} . This shows that at the ϕ at which the maximum K_{st} occurred the peak pressure ratio was 7.4 for SPFT and 7.3 for SPFR. These are large pressure rises indicating that all the coarse mixture had burned and also shows that in spite of the low reactivity of these mixtures, as shown by their low K_{st} , the overpressure was high and would destroy any process plant enclosure used in the processing of this material. These pressure rises were lower than for fine particles of biomass, where for similar biomass composition P_m/P_i was about 8.5 [21, 34].

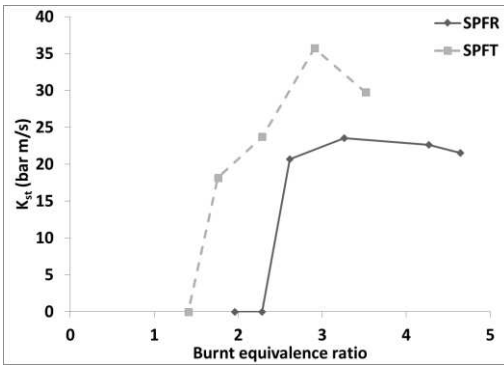


Figure 2. K_{st} v. ϕ_{burnt} for raw SPFR in comparison with torrefied SPFT

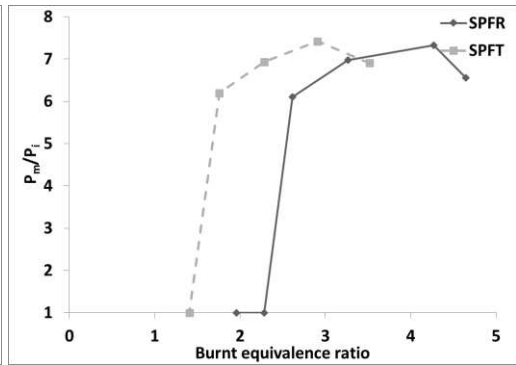


Figure 3. P_m/P_i v. ϕ_{burnt} for raw SPFR in comparison with torrefied SPFT

FLAME SPEED AND BURNING VELOCITY MEASUREMENTS

The measured turbulent spherical flame speeds, S_T , for SPFR and SPFT are shown in Fig.4 as a function of ϕ_{burnt} . These measurements of the mixture reactivity are very similar in their dependence on ϕ_{burnt} as for the K_{st} results in Fig. 2. However, the two peak S_T for the raw and torrefied biomass were very similar at close to 1.0 m/s compared with a significant difference in K_{st} in Fig. 2. This difference may be due to S_T being measured in the constant pressure period of the explosion and K_{st} is measured just before the peak pressure. Fig. 4 also shows that for rich mixtures the flame speed remains high as the fuel concentration increases. This is considered to be explained by the model of the coarse biomass flame front with the flame driven by the finer particles in the mixture and the coarse particles gasified behind the flame front. As more fuel is added the ϕ of the fine fraction flame increases and the temperature of this initial combustion increases this then results in more efficient gasification of the coarse fraction and the gas volume release in the gasification reactions increases which causes the pressure to remain high even though for gases the pressure would fall for richer mixtures.

Figure 5 compares as a function of the mass mean particle size, D_{50} , the present peak S_T with previous [4, 5, 34, 35] measurements of S_T for fine pulverised raw biomass and thermally treated biomass. The previous data was all for biomass sieved to $<63\mu m$ for raw and torrefied biomass (different torrefaction processes) and then analysed for the size distribution. D_{50} as high as $200\mu m$ was found compared with $350 - 450\mu m$ in the present work where the particles were sieved to $<1mm$. Fig. 6 presents the same data in terms of the K_{st} . The terminology for each biomass in Figs. 5-7 has been used in previous publications, but they are all wood based biomass. Fig. 5 and 6 show that the present results for coarse based biomass are consistent with previous results with a prime dependence of the mixture reactivity on the particle size. When compared at the same D_{50} , the difference in mixture reactivity between the raw and torrefied biomass was small, with the torrefied biomass having a slightly greater dependence on size, mainly as a result of the present results. The laminar burning velocity, U_L , of a dust/air mixture was determined from the measured S_T in Fig. 7 by dividing by the calibrated turbulence factor for the ISO 1 m^3 using the calibrated turbulence factor of 4.7 and then using Eq. 2. The results are shown in Fig. 7 and show very low values of U_L for the coarse particles in the present work.

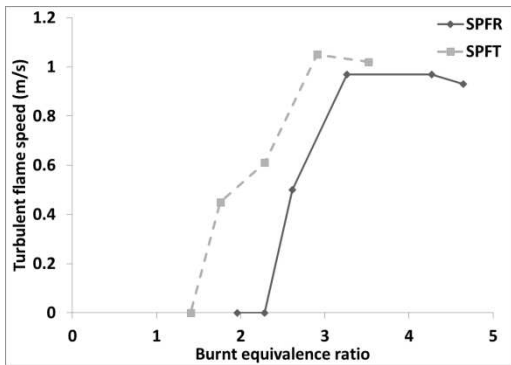


Figure 4. Turbulent flame speed, S_T , v. ϕ_{burnt}

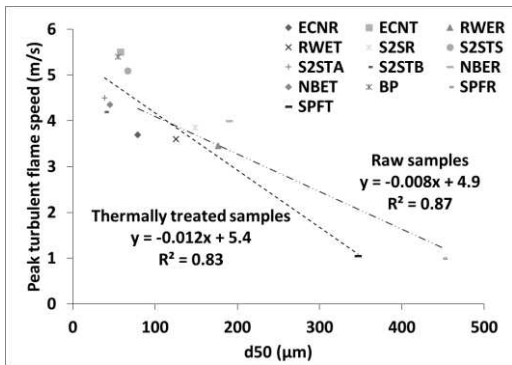


Figure 5. Maximum S_T v. d_{50} for present in combination with other results

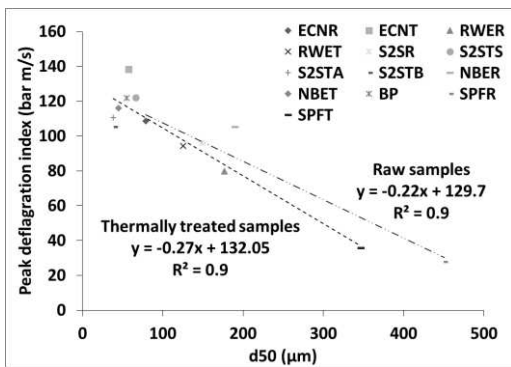


Figure 6. Peak K_{St} v. d_{50} for the present results compared with a range of other biomass and torrefied biomass

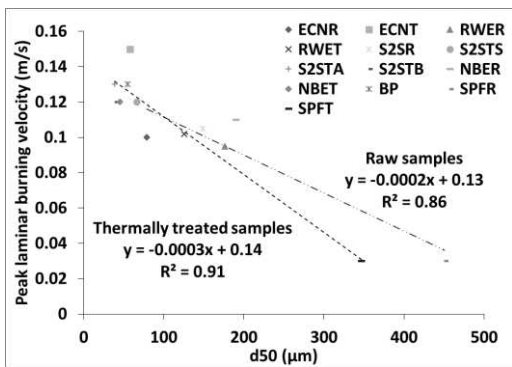


Figure 7. Peak laminar burning velocity, U_L , as a function of d_{50} for present in combination with other results

MINIMUM EXPLOSION CONCENTRATION, MEC

The MEC of the coarse SPF raw and torrefied biomasses were determined from Figs. 2-4 to be 2.3 and 1.4 ϕ_{burnt} respectively. These lean flammability limits were much higher than other biomass for finer sieved fractions, where mixtures as lean as 0.2 ϕ were flammable [4, 21, 34, 35]. The explanation for the richer MEC with coarse biomass is that given above. The flame propagated in the fine fractions blown ahead of the flame by the explosion induced wind and the coarse particle drag leads to these particles burning behind the initial fine particle flame front and being gasified in the burnt gases. For the raw SPF particles Table 2 shows that the fine fraction is 11% of the total mass and the overall MEC is then 1.8 ϕ , which is close to the measured MEC. For the torrefied coarse SPF biomass the fine fraction is 15% and if the fine only MEC is 0.2 ϕ then the overall MEC is 1.3 ϕ , which is in good agreement with the measured MEC.

CONCLUSIONS

Raw and commercially torrefied SPF biomass samples were investigated for very coarse fractions, <1mm, using an ISO 1 m³ explosion vessel modified and calibrated to enable coarse woody biomass samples to be dispersed. The size distributions of the sieved samples show that the

torrefaction process produced finer fractions than in the raw biomass and this led to the torrefied samples having a leaner MEC and higher reactivity at leaner mixtures than for raw samples. Both biomass exhibited explosions, but only for rich mixtures. The peak Pm/Pi were 7.4 bar for both biomass. Post explosion residues showed almost the same composition and size distribution as their parent samples, indicating that they were the parent material. The equivalence ratio at the flame front was taken as the initial mass of dust minus the residue, ϕ_{burnt} . A model was proposed for coarse biomass flame propagation whereby the flame propagated in the fine fraction and the coarse particles were gasified in the burnt gases behind the fine particle flame front. This explained the MEC results and the most reactive mixture being very rich.

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