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Flame Propagation and Burning Characteristics of Pulverized Biomass for Sustainable Biofuel

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Abstract

One of the critical energy challenges, that our planet is confronting today, is how to curtail the reliance on fossil fuels for a sustainable environment. Biomass is a promising source of renewable energy for sustainable power generation compared to the conventional coal. However, they are hard to mill to finer size due to their fibrous nature. In this study, the size dependency on the flame propagation and burning characteristics of pulverized biomass is examined compared to coals. Modified Hartmann and 1m^3 explosion vessels were used to perform flame speed and explosion tests. Fine sized particles propagated the flame with a flame velocity of 2.5 m/s for non-spherical shaped particles compared to rounded shaped Licopodium and cornflour. For coarse size particles, the flame speeds were measured to be around 1 m/s. The minimum explosion concentration was measured to be 0.2-0.4 equivalence ratio for a size range of 40-200 microns and higher for larger particle sizes. Reactivity data showed functional correlations for selected biomass and coal samples. SEM images of post-explosion residues showed incomplete combustion of bigger particles and formation of the cenosphere because of siliceous contents. The study findings concluded that the fine sized particles of biomass had higher fire/explosion risk due to greater burning characteristics and it could only be replaced with conventional coal after assessing their combustion data by reliable methods.

Keywords: Biofuels; Combustion; Explosion; Reactivity; Flame propagation; Activation energy

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Nomenclature

A	Air	S	Flame speed (m/s)
d	Diameter/Size	SEM	Scanning electron microscope
dP/dt	Rate of pressure rise (bar/s)	SMD	Surface mean diameter (μm)
F	Fuel	SPF	Spruce, Pine, Fir
K	Deflagration index (bar·m/s)	T	Temperature (K)
MEC	Minimum explosive concentration	TGA	Thermogravimetric analysis
P	Pressure (bar)		

Special symbol

$Ø$	Equivalence ratio

Subscipts

m	Maximum	p	Constant pressure
o	At the start	st	staub/dust

1. Introduction

Using fossil fuels for combustion results in the hazardous emissions to the atmosphere and their return through acid rain affect the living environment [1, 2]. The harmful gases, including carbon dioxide and sulphur dioxide turned to acids after mixing with rainwater that is hazardous [3]. The utilization of coal was discouraged to protect the environment from toxic emissions [4]. There were great concerns about the first use of coal in China that affected human health [5]. In the past, the UK was fulfilling its energy needs from coal, and coal power generation plants were sharing 31% of the country's electricity needs [6]. Coal power generation plants are shutting down due to their deterioting effect to the nature. To save the capital investments of the existing coal power generation plants, some of them had been switched to renewable wood [7]. Dependence on coal in 2014 has suppressed to 36% compared to 2013. Provisional Department of Energy and Climate Change (DECC) estimated the carbon dioxide emission reduction of 9.7% in 2014 compared to 2013 [6]. There are limited combustion and flame speed data for biomass that need to be established first before it is used for energy applications instead of coal in the power generation plants.

Biomass materials are more diverse, with a wide variation of their chemical characterization [8, 9]. Also, these biomass fuels are voluminous and have less heating values as compared to coals [10]. Agricultural waste biomass have limited applications as adsorbent, and energy source because of higher inert and impurity like ash + moisture contents in their structures [11, 12]. Presence of silica and alumina results in the poor combustion forming cenosphere [13]. Application of some pre-treatments refines this sustainable fuel [14, 15]. Pelletization, along with torrefaction or steam explosion, reduces the amount of moisture with resultant materials of unique properties [16, 17]. However, these pre-treatments specially thermal treatments are costly. There has to be a trade-off of investments in carrying out these pre-treatments and the resultant benefits in terms of higher heating values, easy handling, and transportation with low-cost milling.

It was observed that these biofuels were more reactive compared to coal samples, and this was due to the fast release of volatiles at the low temperatures. Activation energies using John Stagg's quick approximation method for the biomass samples were determined to be in the range of 60-90 MJ/kmol as compared to 110 or higher for coal samples [18]. About 90% of the volatiles were released at around 400°C for biomass samples due to their soft and porous structure, whereas the same proportion of volatile was released at around 750°C for coal samples that is 350°C higher [18].

This volatiles yield is essential in the flame propagation, and therefore the characterization of these volatiles was key for the development of combustion model of biomass [19-21]. The release of volatiles and their chemical characterization depend on the heating temperature and heating rate. As higher heating temperature and heating rate accelerate the rapid release of volatiles composed of reactive gases like H_2 and CO [22].

Due to the higher reactivity of these biomass fuels, they pose fire and explosion hazards in their handling [23]. Also there is scarce data available in the literature for the burning characteristics of these biomass fuels. Lots of biomass fire/explosion incidents had been reported in the past and still happening for scarce data of their burning characteristics. On average, one dust fire/explosion incident of low or high intensity occurs each day in the biomass plants [24, 25]. A very latest incident of biomass dust explosion occurred in Macclesfield, UK that resulted in the deaths of four peoples and a significant physical loss. The fire broke in the wood treatment facility with the subsequent explosions. The spark blaze was risen to a height that was visible from 18 miles away. Some recent fire/explosion incidents in the biomass plants were listed in Table 1 [26]. The reactive concentration, when converted to equivalence ratio, could be used to compare the lean, stoichiometric and rich concentration with other liquid and gaseous fuels (Andrews and Phylaktou 2010).

Table 1 Recent biomass dust fire/explosion incidents [26]

Type	Plant	Summary
Fire	Polish pellet factory	• Straw fire broke out in a pellet factory • Fire spread to several heaps of straw • Situation was under control after efforts of fire fighters.
Fire	Wood chip factory, France	• Wood chip factory premises caught fire • One was killed while six workers injured.
Explosion	Furniture plant, Canada	• Fire and dust explosion were reported in dust hopper. • One fire fighter was injured.

Size distributions of biofuels also play a critical role in flame propagation. As it was found that Pittsburg coal sample with particle size greater than 200 µm was not explosible [27] but biomass samples with particle size distribution even coarser than 200 µm were propagated the flame [13, 28]. It was found in testing different size range fractions of biomass that they were able to sustain the flame of size range as high as 300-500µm depending on the biomass. Sample of the SPF wood mixture and its torrified form, provided by british wood company 'Renewable fuel technology', were tested by the author exploded for <1mm size range fraction. However, the post-explosion analysis revealed the preferential burning of fine particles with partial combustion of coarse particles [29]. The reactivity of these biofuel dust flame propagation was underestimated, and the replacement of coal with this biomass can be unsafe for the power generation plants. The wrong assessment of their burning characteristics can lead to fire or/and explosion incidents. Also, the inaccurate flame speed and burning velocity can cause the back flash in the burner.

Biofuel is reactive fuel with higher flame propagation and burning characteristics compared to coal that was the focus of this work. Particle size plays a key role in the burning rate and flame propagation acceleration. Assessing their burning characteristics in terms of equivalence ratio, peak pressure rise and flame speed against their particle size distribution are described in this work. The higher reactivity of these biomass samples was evaluated that can be useful for the modification in the existing design of power generation plants in coal replacement.

2. Materials and Methods

Modified Hartmann tube and 1 m^3 vessel were used for the study of biomass flame propagation of various size range fuel fractions, as shown in Figure 1. The fuels were sourced from Pakistan and UK origin for the testing. These fuels were washed, dried, milled and sieved to get different size range fractions in the explosion and testing lab of the University of Leeds, UK.

1L vertical modified Hartmann tube with 322mm length and 61mm inside diameter was used for the measurements of burning characteristics. The effect of particle size in the formation of flame and its propagation was recorded photographically. A high-speed camera with 5000 frames per second with an accuracy of 5 frames per millisecond was used to visualize the distribution and flame propagation of dust samples. Three thermocouples above spark were used to record the time of flame arrival for flame speed measurements. Modified 1 m^3 vessel with the specification of ISO 6184/1 (1985) was also used for different size range fractions [30] and the explosibility results were compared with fine coal samples. Two Keller type-PAA/11 piezo-resistive pressure transducers were used for recording pressure rise. These pressure transducers had an accuracy of 99% calibrated by the factory and a response time smaller than <1ms for measurement of pressure rise. Three-dimensional arrays of thermocouples were also placed in the vessel to record the time of flame arrival for flame speed measurements the same as in the Hartmann tube. These minerals insulated exposed junction K-type thermocouples have less dead time for their response because of their minimal thickness.

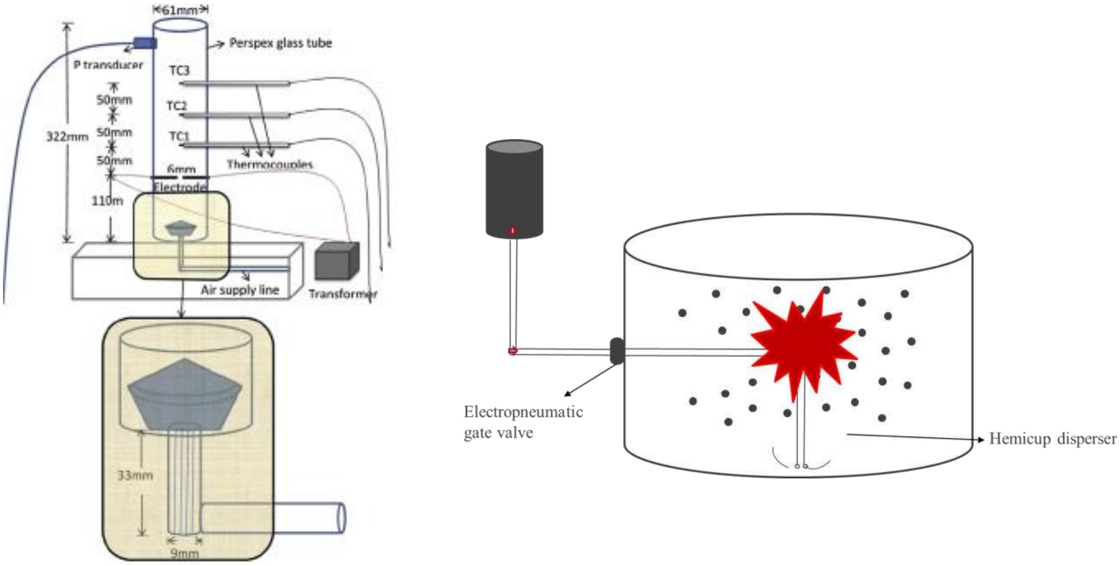


Figure 1. Schematic diagram of the modified Hartmann (Left side) and 1 m^3 vessel (Right side)

The delay in the voltage rise of these thermocouples with an increase of thermal energy was irrelevant as they were only used for recording the arrival time of flame passing through these thermocouples. Flame speeds were measured by plotting the relative distances of unidirectional thermocouples vs. time of flame arrival and taking the slope for unidirectional flame speeds. This method of three-dimensional arrays of thermocouples in 1m^3 vessel also confirmed the uniform flame propagation in the vessel. The accuracy of the repeat dust tests for pressure measurements was recorded to be almost 95% with 5% variation, and for deflagration index 'K_{st}' was about 92% with 8% variation. Other authors also performed repeat tests with different dusts, and the accuracy of reactivity measurements was above 95% for pressure measurement and above 90% for K_{st} measurements. Details of these and experimental methodologies had been explained in published works [10, 31-34].

Reactivity in terms of equivalence ratio was more appropriate as it helped to compare the burnt concentration in comparison to stoichiometric concentration. Stoichiometric equivalence ratio was calculated based on simple elemental and proximate analysis using the following formula;

$$Stoichiometric\left(\frac{F}{A}\right)=\frac{(12+y+16z+14w+32k)}{\left[\left(1+\frac{y}{4}\right)-\frac{z}{2}+w+k\right]\cdot 137.9} \qquad [1]$$

Where y, z, w, k are the molar ratios of hydrogen, oxygen, nitrogen, and sulphur respectively relative to Carbon and 137.9 is the molar mass of air.

The elemental analysis was performed using Flash 2000 Thermo Scientific analyser after averaging the two repeat tests for each sample. The percentage oxygen was calculated by the difference method. Proximate analysis was performed using TGA-50 shimadzu analyser using a temperature program [13]. The data for the cumulative curves for the different size range fractions were acquired by laser diffraction technique using Malvern Mastersizer 2000.

3. Results and Discussions

3.1 Flame propagation through fine biomass dust in comparison to fine coal particles

In Figure 2, the night vision of flame propagation was captured of fine biomass yellow pine dust in comparison to Columbian Coal for size range distribution of less than 63 microns. It was visualized that there is a uniform flame for biomass due to high volatile contents, whereas, for coal, there was discontinuous flame propagation. Vent bursting because of pressure build-up was reached quickly for biomass compared to coal samples. This was understood for the hard structure of coal that delayed the release of volatiles for instant flame propagation.

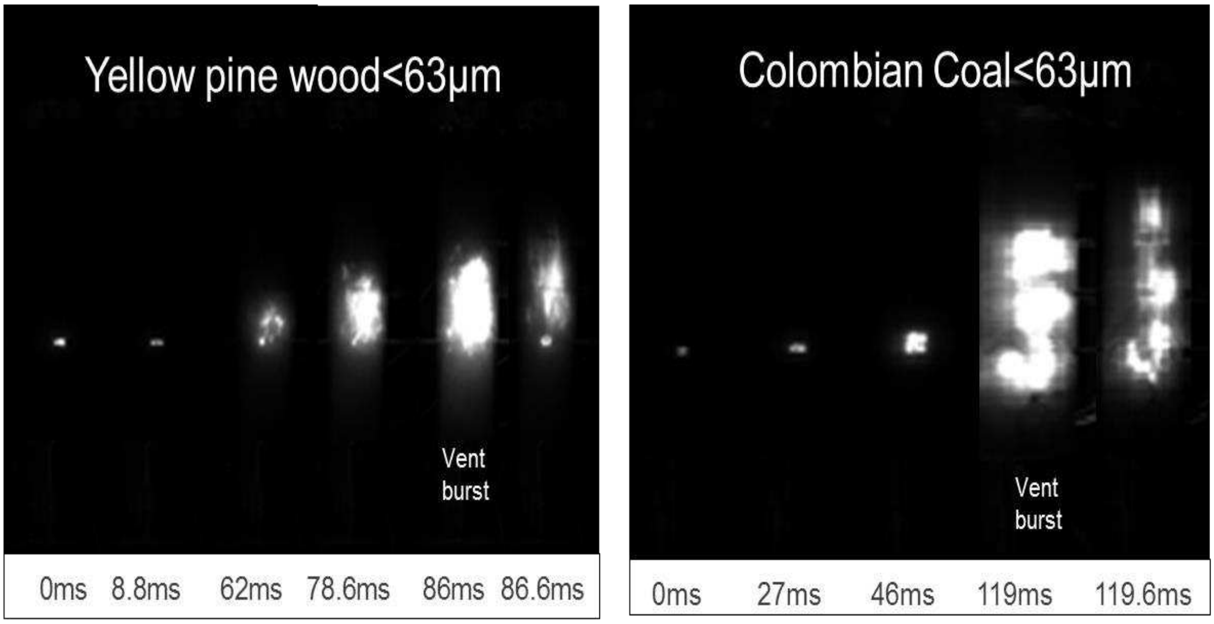


Figure 2 Flame visualization of fine wood dust in comparison to Coal sample

Flame speed data, as shown in Figure 3, of different biomass and coal dusts from the previous research work by the Leeds fire and explosion group is plotted against their particle size, d_{50} for particle size distribution less than 63 microns [10, 29, 34-36]. The dust samples having higher proportions of fine particles showed higher flame speeds up to 12 m/s and lower flame speeds of about 1 m/s for the samples with least proportions of fine size particles (less d50). Coal samples and raw SPF (sawdust, pinewood, and fir mixture) showed the least flame speed data of 1-1.3 m/s against particle size of 400 micron d_{50}. For most of the tested biomass, the flame speeds were measured to be in the range of 3.7 to 5.5 m/s for a smaller particle size range. Along with size, the shapes of the particles also an essential parameter in the propagation of flame. Biomass particles are thin and of irregular shape, as was also viewed by SEM images shown later in this work.

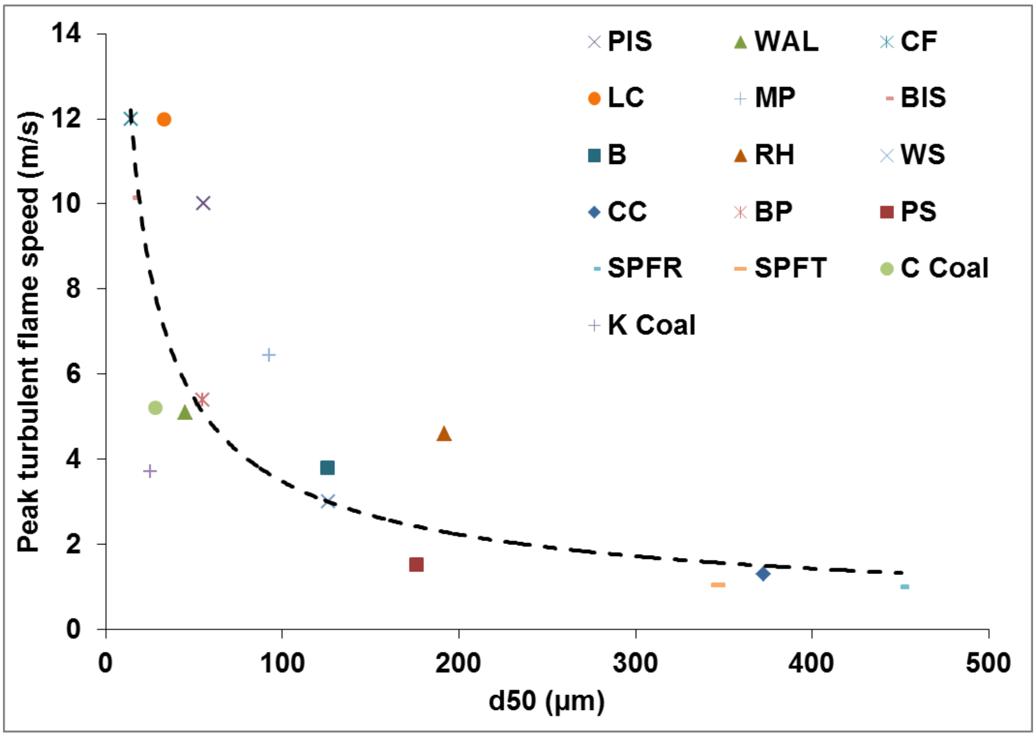


Figure 3 Effect of particle size on the lean flammability limit of different biomass samples [10, 29, 34-36]

As shown in Figure 4, the minimum explosive concentration in terms of equivalence ratio was plotted against the average particle size distribution of different sized Rice husk samples. It was found that the minimum explosive concentration (MEC) was increasing from fine to coarse size range fraction with increasing average particle size. Rice husk samples have brittle ash that enriches the fine sized fraction. This inert ash cools down the flame temperature and showed same MEC for size below 100 microns using Hartmann tube. However, for 1 m3 vessel, due to strong ignition source, the finer fraction showed leaner MEC despite of the higher inert ash.

The fraction of higher average particle size ignited after the release of enough volatile for sustainable flame propagation. The slope became steeper from fine to coarse size ranged samples with more mass of sample required for their explosion. For finer sized Rice husk fractions, the minimum explosive concentrations were lower than the coal samples and other HC gases using both Hartmann and 1m3 methods.

In reference to Figure 4, the severity of the explosion was proportional to the small particle sizes with higher exposed surface areas for the instant release of volatiles for efficient combustion. The consequences of effective burning of these fines cause more destruction due to their rapid and complete burning. As fine particles have high exposed surface area than the coarse size easing the volatile release for combustion. The fire and explosion hazard level against particle size along-with inert was shown in Figure 5 based on the findings of the authors.

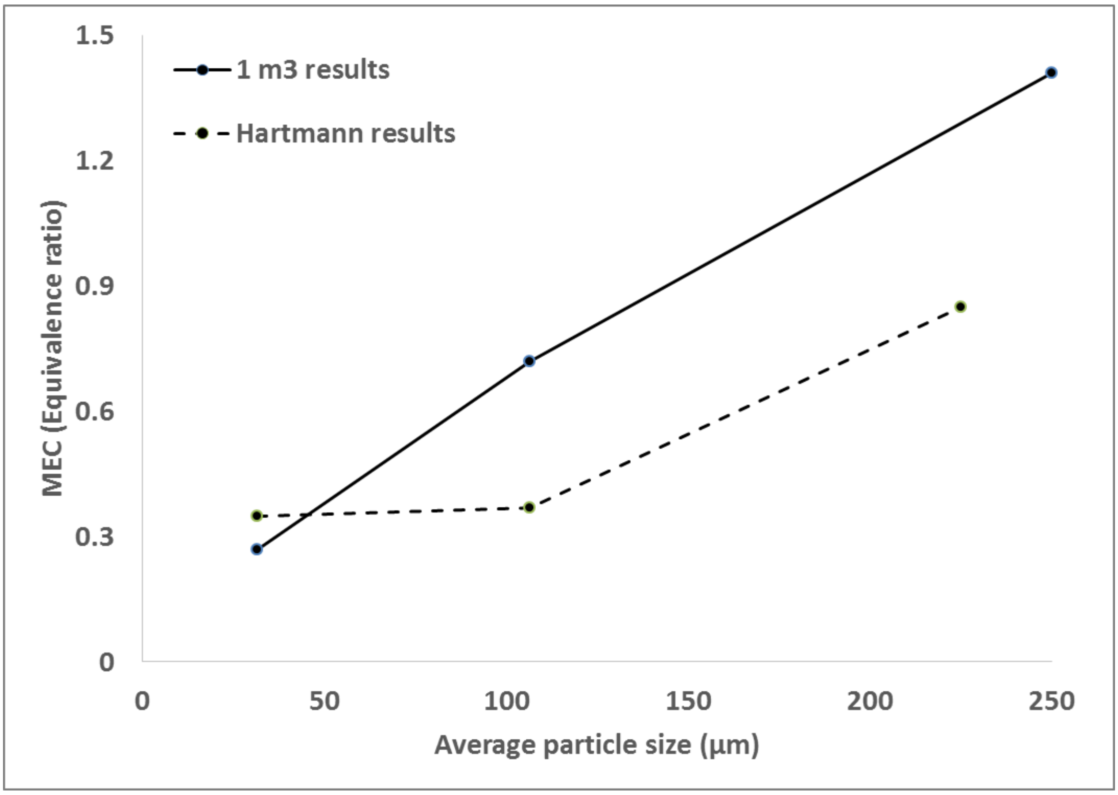
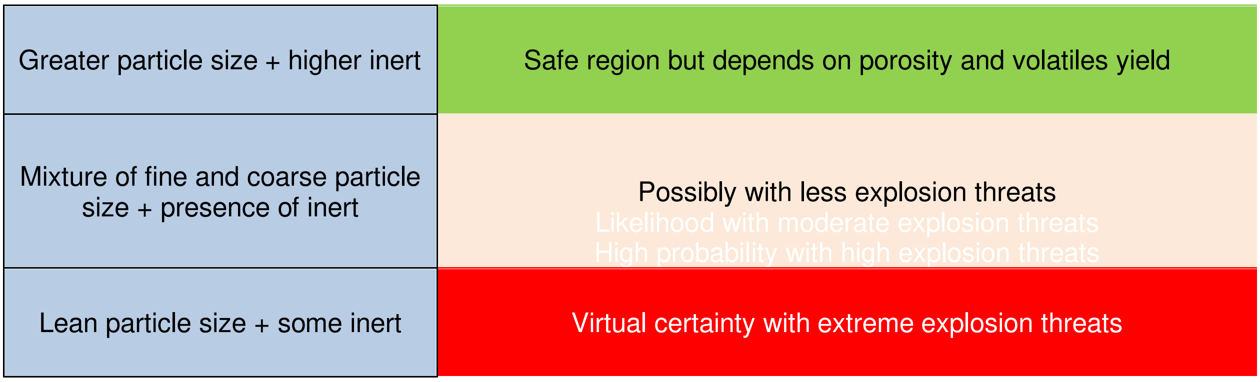


Figure 4 Effect of particle size on the MEC using Hartmann and 1 m^3 vessel for different sized Rice husk samples



Greater particle size + higher inert	Safe region but depends on porosity and volatiles yield
Mixture of fine and coarse particle size + presence of inert	Possibly with less explosion threats Likelihood with moderate explosion threats High probability with high explosion threats
Lean particle size + some inert	Virtual certainty with extreme explosion threats

Figure 5 Explosibility threats of biomass with different particle size distribution and inert

3.2 SEM Morphological study and Particle Size Distribution

Rice husk biomass sample was found to have cylindrical fibrous particles with a wide variety of particle size distribution as shown in Figure 6. This is in contrast to the coal samples with smaller particle size and less variation of particle size distribution. Surface morphology showed that there were tiny holes on the surfaces of fibrous biomass particles. This higher porous structure of biomass results in the higher release of volatiles.

Particle size distribution of the same Rice husk biomass sample, see Figure 7, were compared for raw and post explosion residues for three particle size ranges as RH less than 63 micron, size in between 63 and 150 microns and smaller than 500 microns. It was found that for the fine size range sample (less than 63 microns), the particle sizes for the post explosion residue was greater than the raw sample. This was due to the maximum combustion of fine size particles leaving coarse particles in the residue. For medium particle size range (63-150 microns), the particle size of raw and post explosion residue samples were found to be almost comparable for higher proportions. For large particle size fraction (Greater than 500 microns), the post explosion residue sample was found to be finer than its raw sample. The situation was reversed as the thin large particles might shatter during flame propagation and resulted finer size fraction for the post explosion residue.

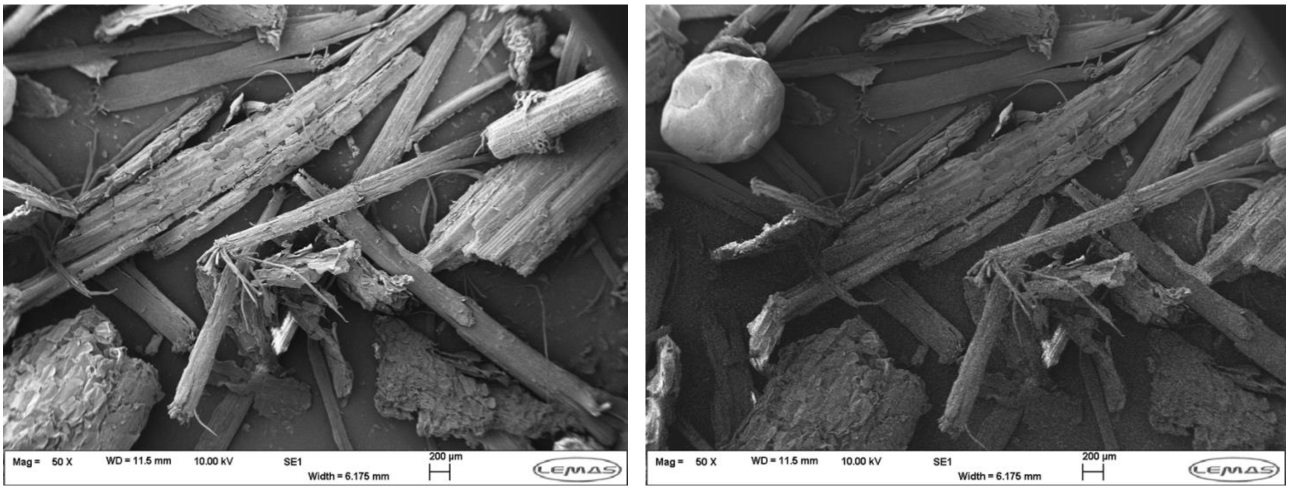


Figure 6 Surface morphology of raw Rice husk sample

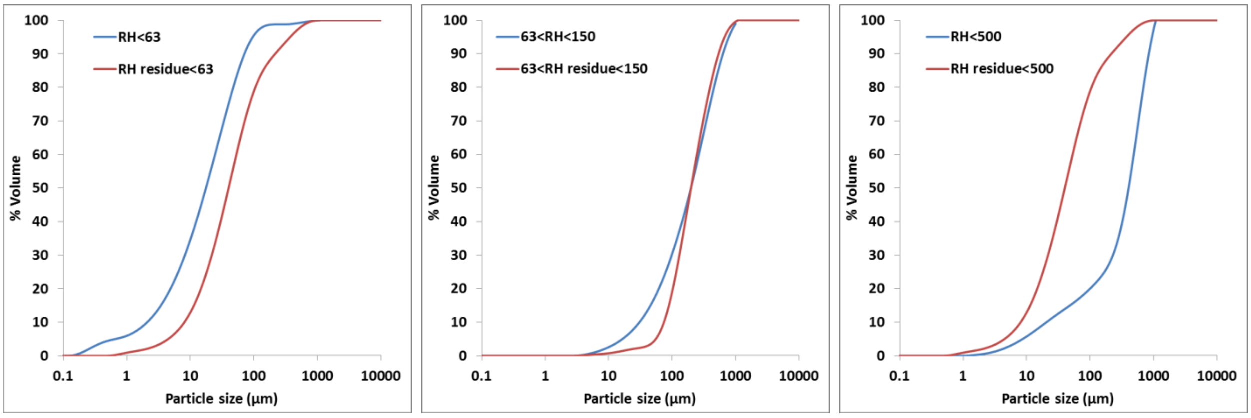


Figure 7 Particle size distribution for raw Rice husk and its post explosion residue sample for three sieve size ranges (less than 63 micron, 63-150 microns and smaller than 500 microns)

3.3 Peak turbulent flame speed vs. peak dP/dt of different size range biomass samples

Different biomass samples of varying size range fractions showed better correlations of peak turbulent flame speed and peak rate of pressure rise using Hartmann tube, as shown in Figure 8. These correlations showed that the peak reactivity of different biomass samples increased with increasing fine particle proportions. The varying sized Rice husk samples showed linear correlation of peak flame speed with dP/dt,

Similarly, three wood samples, pinewood pellet named, HW sawdust named, and construction wood waste 1 were split into following size range fractions of <63µm, 63-500µm and <500µm. The fraction with more fine particles like < 63µm was more reactive than <500µm fractions, and samples with 63-500µm fraction with least fines showed less peak reactivity. It was also noted that wood samples showed higher peak turbulent flame speed compared to crop residues that might be due to less inert, but more fines in crop residues resulted in fast combustion with the quick rise of peak pressure.

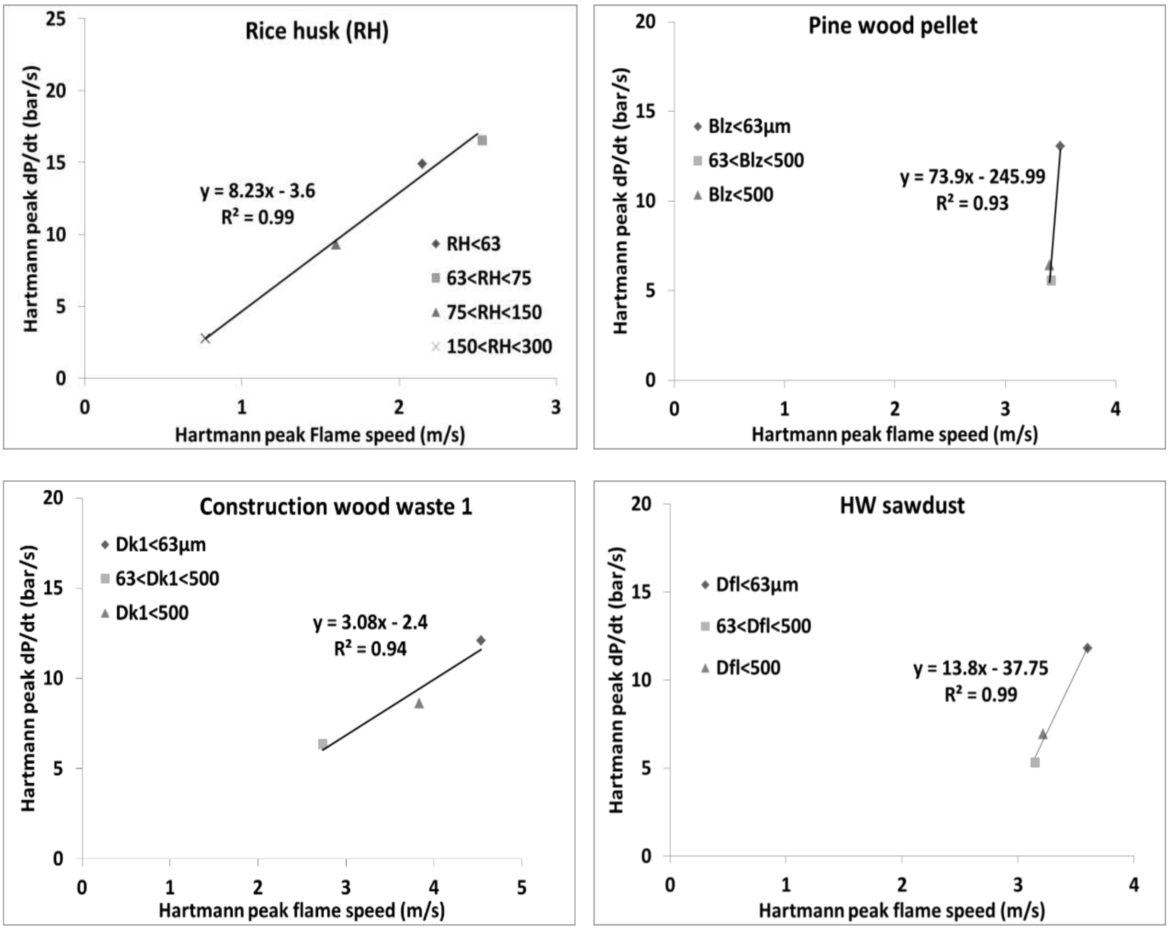


Figure 8 Peak reactivity correlations of different biomass samples for varying particle size distribution

Rice husk samples with enough quantity to do 1 m^3 tests was split into different size range fractions. Peak turbulent flame speed showed an excellent correlation with peak deflagration index for different size range fractions, as shown in Figure 9. A big difference of peak dust constant and peak turbulent flame speed were observed for <63µm and 63-150µm fractions due to the difference in the proportions of fines in these fractions.

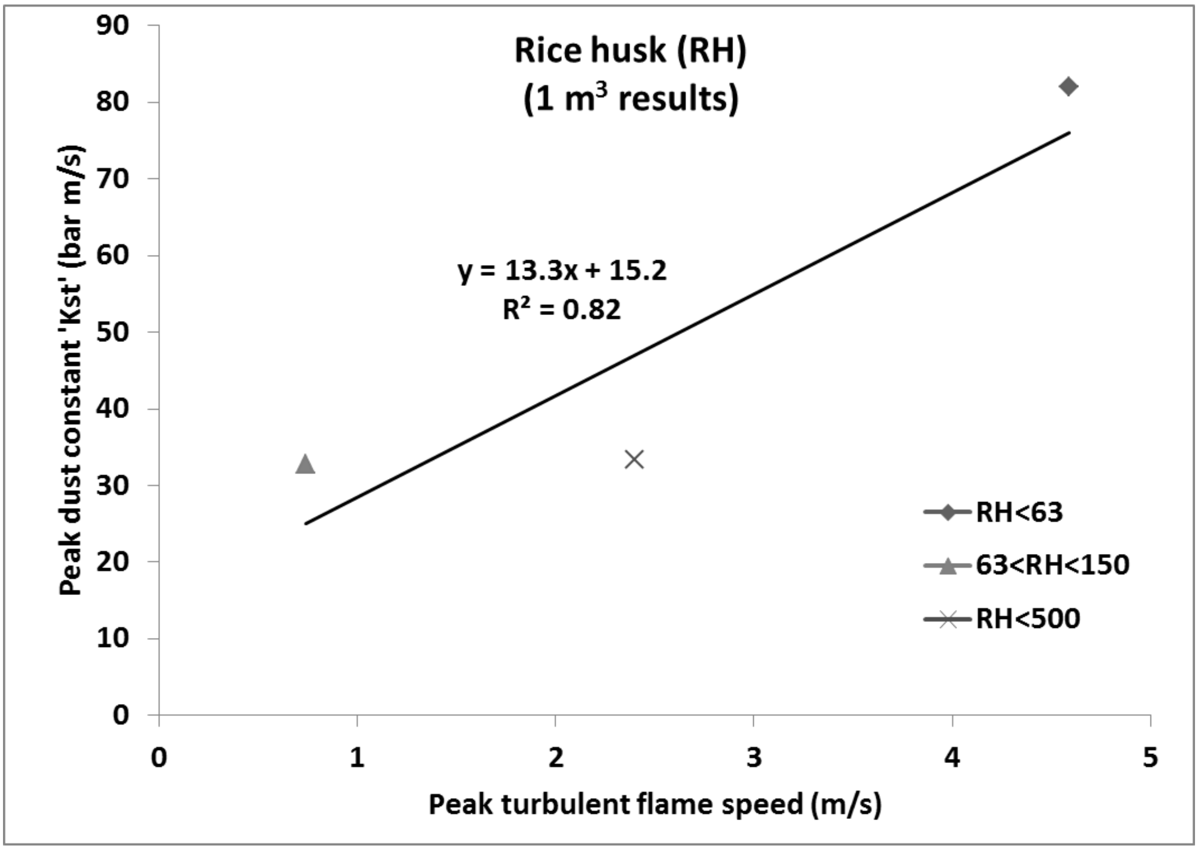


Figure 9 Peak dust constant vs. peak turbulent flame speed of rice husk in 1m^3 vessel

3.4 Reactivity of biomass in comparison to coal samples: Multicomponent analysis

Deflagration index 'K_{st}' and flame speed of different biomass and coal samples depend on multiple parameters like the composition of sample volatiles yield, particle size, structure softness, inert, and environmental conditions. High volatiles, soft structure, small inert, and small particle size boost the combustion reaction and vice versa. Also, some biomass samples despite the same size distribution of < 63 µm showed different sizes of 10%, 50%, and 90% proportions of the sample in Malvern Mastersizer. There is a cumulative effect of various parameters on the reactivity of biomass samples. Some coal samples were found to be more reactive than biomass, however, some were less reactive. However, due to high volatiles yields and soft porous structure of biomass, they were mostly found to burn leaner with small minimum explosive concentration than coals despite the greater size of the particles e.g., Bagasse, rice husk, and wheat straw sample despite higher inert in terms of ash and moisture were found to have leaner minimum explosive concentration than the Colombian and killingly coal samples for less than 63 µm samples.

It was found that higher volatiles yield per unit inert resulted in the higher volume normalized rate of pressure rise. However, despite higher volatiles yield per unit inert, the large particle size distribution fraction took longer to release enough volatile for flame propagation so there is a counterbalancing effect of larger particle size on the reactivity. The effect of particle size based on d50 on the reactivity is plotted, as shown in Figure 10. It was found that small particle size distribution facilitated the fast reaction giving the higher K_{st}. However, the softness and porosity of the surface were still not accounted for in this analysis. Colombian coal showed the highest reactivity with maximum dust constant for higher volatiles yield, lower inert, small particle size distribution, and the soft structure that facilitated the release of volatiles.

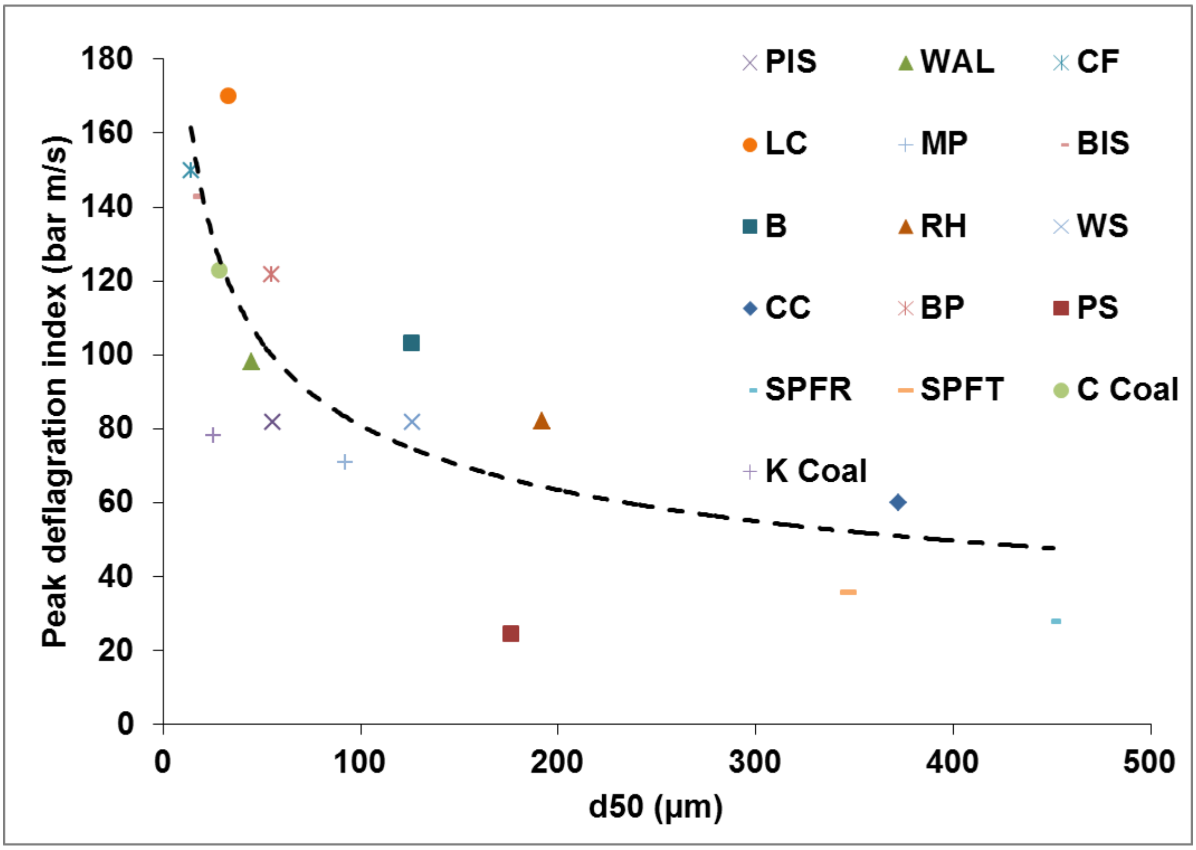


Figure 10 Variation of reactivity as a function of d50 particle size [10, 29, 34-36]

Bagasse, compared to Colombian coal, was less reactive due to larger particle size despite the higher volatile yield. Rice husk has a higher volatile yield, but coarse size fraction in comparison to wheat straw resulted in the same reactivity for these two samples. Kellingley coal was found to be least reactive compared to others due to small volatile yield and higher inert that suppress the efficient reaction.

Comparison of burning properties of biomass in comparison to coal samples compared, as shown in Table 2. It can be seen that some biomass samples have similar, higher or smaller pressure rise relative to ambient atmospheric pressure, dust constant, peak turbulent flame speed, most reactive concentration and lean flammability limit based on volatiles yield, particle size distribution and inert present in them. There was more mass burning of biomass in less time as compared to coal samples due to the soft porous structure. Most reactive concentrations were at higher equivalence ratio than a stoichiometric concentration of '1' in terms of corrected burnt equivalence ratio. Only rice husk sample showed the most reactive concentration at stoichiometric concentration, but due to a limited amount of dust, tests could not be run for further higher equivalence ratio as in 1m^3 vessel. It requires dust in kg for performing a test of rich concentration.

Table 2 Comparison of explosibility characteristics of biomass in comparison to coal for <63µm sieve size fractions using modified 1 m^3 vessel

Samples	*Ø$_{peak\ kst}$*	*Peak Pm/Po*	*Peak K_{st} (bar m/s)*	*Peak turbulent flame speed (m/s)*	**MEC (Corrected Burnt eq. ratio)**	*References*
Rice husk	1.0	7.3	82.0	4.6	0.27	This work
SPFR wood (Raw wood<1mm)	4.4	7.3	28.0	1.0	2.3	This work
SPFT wood (Torrified wood<1mm)	2.9	7.4	35.7	1.05	1.4	This work
Bagasse	2.7	8.8	103.1	3.8	0.18	[13]
Wheat Straw	1.6	8.5	81.7	3.0	0.24	[13]
Black pellet	1.1	8.6	121.7	5.4	0.14	[34]
Pistachio nut shells	2.4	9.3	82.0	3.7	0.37	[35]
Walnut shells	2.8	9.4	98	5.1	0.31	[35]
Southern Pine 1	4.2	9.0	105.0	3.7	-	[36]
Pine 1 (torrefied)	2.2	9.1	138.0	5.6	-	
Norway Spruce	-	9.0	96.0	3.8	-	[37]
Spruce (torrefied)	-	9.1	110.0	4.6	0.33	
US Pine 2	2.5	9.0	105.0	4.5	-	[37]
US pine 2 (torrefied)	2.0	8.8	115.0	4.4	0.33	
Colombian Coal	2.6	8.2	122.9	5.2	0.39	[36]
Kellingley Coal	2.3	7.9	78.2	3.67	0.45	[36]

3.6 Practical Implications of this Study

Using biomass dust as fuel for power generation plants can be extremely hazardous because of higher volatiles yield and its release rate. In this work, the explosibility and flame propagation properties of the selected biomass dust in comparison to the coal samples are discussed. The outcome of this research work is that the finer the size of biomass, the more reactive it is. However, it must be dealt with complete fire/explosibility data. The results outlined in this research work are only for the selected, tested biomass samples and dependent on the type and source of the biomass for a wide diversity in the chemical characterization. For coarse size dust particles, the flame propagation is difficult to measure with the standard system of dust explosibility tests. For coarse size biomass, the calibrated dust dispersion system can gather the explosibility data. This data is used for the modification in the existing design of burner in the coal power generation plants that must be shifted on renewable fuels like biomass. Also, the optimum flow of fuel and air must be set for the steady flame to avoid the flashback in the dust dispersion system. So, the reactivity data of the biomass dusts in terms of its explosibility characteristics and flame propagation is extremely critical for their safe application as fuel.

4 Conclusions

In this work, different biomass samples of varying size ranges were compared with coal samples for their combustion and explosibility characteristics keeping external environmental conditions constant. Higher volatile yield and their faster rate of emissions at lower temperatures facilitate the early combustion of biomass as compared to coal samples. Fine biomass particles were proved to be more sensitive to explosion as compared to coarse size fraction. SEM imaging study showed the involvement of more fines with their preferential burning for effective flame propagation. Also, post-explosion residue samples of biomass and coals showed partial burning of the coarse or porous structure because of volatile loss. Multiple parameters were affecting the development and propagation of flame with their positive and negative effects. Biomass samples in comparison to coals were found to have higher reactivity with their instantaneous burning characteristic in dust clouds and with leaner flammability limits that must be addressed before their exploitation as a substitute for coal in the power generation plants.

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