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Ignition and combustion of single particles of coal and biomass

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Abstract

Co-firing technology at large power plants can contribute to reducing emissions and maintaining stable and secure electricity supplies. Due to the higher reactivity of biomass, a larger particle size range is generally used for biomass fuels compared with pulverized coal. A single particle apparatus has been developed for rapid heating and combustion of individual fuel particles. This wire mesh apparatus was used as a heating element to heat the particle by radiation while optical access allowed particle combustion characterization by high speed camera recording. A woody biomass and a bituminous coal were used in this study. Both fuels showed a sequential combustion of volatile matter followed by char combustion. High speed video image analysis showed differences in ignition and devolatilization behaviour. The biomass volatile flame was smooth along the overall particle, while coal volatile matter release was delivered by jets. Times for the volatile matter combustion were much shorter for the coal while pyrolysis seemed to be the dominant step for around half of total combustion time. During devolatilization, the bituminous coal showed a significant swelling that was not seen in the biomass. As particle mass increased the overall times required for drying, devolatilisation and burnout increased for both samples, and this was the dominant parameter to predict burnout time. Impact of particle size and mass was much higher in coal, with a dramatic increase of the burnout times for particles above 300 μm , while biomass particle size can have a greater range

of sizes for the same burnout times. During biomass particle combustion, the results showed that the surface tension on the biomass char particle plays a significant role due to partial melting of the char particle. This effect modifies the char particle shape during its combustion, with particles becoming more spherical particle even for the initial fibrous shape of the woody biomass particles.

Keywords: coal, biomass, single particle combustion, Wire mesh reactor, ignition, high speed recording

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1. Introduction

Biomass is considered to be a promising source of renewable energy for mitigating climate change. Biomass power plants as well as coal and biomass co-firing power plants could provide large scale reliable energy with the flexibility to meet potentially unpredictable demand for electricity. Co-firing technology has to overcome some technical complications due to the differences in the fuel properties and behaviour in the combustion. Research is needed to improve the technology available in biomass renewable power to progress in the development of more efficient and cleaner combustion. Detailed investigation in the ignition and combustion of the diversity of biomass materials is needed to establish any differences that may affect the design of burners and furnace performance when co-firing coal with biomass fuels.

Different biomass fuels have been used for research and different types of pilot plants depending also on the wide range of physical and chemical properties of the fuel [1]. The standardization of biomass fuel in the form of high energy-density pellets allows easier managing and a more sustainable transport to all scales consumers [2]. This also facilitates reliable performance of the combustion with constant ash content and calorific value of the fuel. This has been key to the development of modern biomass boilers and biomass-fired combined heat and power (CHP) plants, especially small scale biomass heat and power. Certified quality pellets ensure low ash, sulphur and moisture content and a minimum energy density. However large scale power plants need to allow some flexibility in the fuel quality given the amount of fuel typically required. Fuel flexibility can also help to facilitate cost reduction.

Single particle devices have been successfully used in previous studies [e.g. 3] to undertake comprehensive studies of coal combustion and have identified the differences between coals depending mainly on their rank. Lignite [4] and anthracite [5] coals have been reported to burn

as a one step process with the heterogeneous combustion of the particles, while bituminous coal show a volatile flame prior to char combustion. The main different single particle setups, summarized by E. Marek in [3], have been used to provide proper description of the combustion process. The implementations of the techniques allowed to provide more data like particle temperature [6] or particle aspect ratio during the combustion [7]. More recently single particle studies have considered combustion in oxy-fuel atmospheres, like works done by Levendis et al, Kathami et al and Riaza et al [5] at the Northeastern University. This work has pointed out differences in results obtained when single particle studies are compared to the combustion of fuels that are burnt in a drop tube with different oxygen content. It was found that between the volatiles combustion and char ignition appears a gap time where there appears to be no progress in any combustion reaction in the lower oxygen content atmospheres. This effect was even more pronounced in the O₂/CO₂ atmospheres, producing a delay in the order of 10 milliseconds for the conditions of the study.

When compared to coal, biomass shows high contrast in key parameters, such as ignition temperatures, ignition delay times, and burnout times. Single particle biomass combustion studies are not very common in the literature until recent years. Biomass fuels usually have higher volatile matter content than coals. The biomass pyrolysis also tends to start at lower temperatures than coal, creating a higher volatile release flame when co-firing that leads to lower ignition temperatures [8]. The higher amount of volatiles in the combustion chamber also impacts on coal char combustion as the gases released will contribute to gasification reactions, enhancing the mass lost during the char formation and combustion. Even though the combustion reactions are the main conductor of the flame and burnout.

Flower et al [9] conducted biomass single particles studies in a wire mesh single particle setup. Results for particles between 5 and 30 mg showed relatively low dependency on the

aspect ratio of the samples [10]. P. Mason et al. [11] perform a series of single particle experiments showing a significant influence of the moisture content in particle ignition delay.

Modelling single particle combustion [12] has also been effective in understanding the main variables that affect combustion kinetics. Other works by [13] have studied the effect of the particle size and shape on the behaviour of the fuel. The particle size distribution and its influence on the combustion performance is needed to establish the milling requirements for an effective burning for each fuel, especially for new biomass fuels.

Regarding the milling of the pellets it is usually assumed that the shape and size of the particles after milling the pellets is nearly the same as the original milled wood prior to pelletization. Milling of biomass fuels is inherently energy intensive and the optimisation in terms of minimum particle size for efficient burn-out is still not fully established. Fuel particle distribution has been reported [14] to have a large significance in the power plant operation. For coal power plants the fuel needs to be milled to sizes below 300 μm with 80% below 75 μm . The fuel particles above 300 μm are likely to produce carbon in ash, as the combustion time needed for their total burnout is longer than the residence time.

The objective of the present study was to observe the differences in the ignition and combustion behaviour for particles of fuels by measuring volatile burning time and char combustion time for each particle in order to compare times required for burnout. The study include a range of sizes in order to establish the maximum particle size for a woody biomass that would have the same burnout as a given coal particle. The combustion test data can help to understand the milling requirement of the biomass for an efficient combustion in an industrial boiler. The information provided by the video observation can also provide fundamental data for other researchers developing new models to more accurately describe the combustion process at a particle level.

2. Materials and methodology

2.1. Fuel samples used

The selection of the fuels was based on their wide use in the UK. The coal El Cerrejón (CC) was imported from Colombia and is a high volatile bituminous coal. The biomass sample used was white wood pellet (WWP), was imported from Canada. It has the typical composition of a wood pellet widely used for domestic and industrial heating, with very low ash content, a high volatile matter content and a calorific value much lower than the coal. Proximate and ultimate analysis are given in Table 1.

	Coal El Cerrejón	Biomass White Wood Pellets
moisture content (% wt)	5.5	7.81
ash content dry (% wt)	1.2	0.99
volatile content daf (% wt)	40.1	91.84
fixed carbon daf (% wt)	59.9	8.16
GCV (dry) (MJ/kg)	32.7	17.75
Elemental daf (% wt)		
C	73	51.49
H	5.2	3.14
O	19.6	44.7
N	2.2	0.55

Table 1. Proximate and ultimate analysis of the samples used.

Each sample was milled, dried and sieved to different ranges of sizes. The particle sizes used were between 3 mm to 610 μm for biomass, and 1 mm to 250 μm for the coal sample. Samples were dried in an oven at 115 °C for 2 hours to remove any moisture. Each particle was weighed before experiment using weighing balance six digits balance Sartorius Secura 225.

2.2. Experimental device

The wire mesh apparatus used in this work allows a stationary particle sample to be recorded as it burns with high speed video camera. The single particle apparatus has been developed based on a previous experimental device explained in Flowers et al. [9]. As in the previous

studies the samples under test were held between 2 vertical wire mesh that act as electric heating elements. The heating of the particle is largely by radiation by 2 large 40×40 mm wire mesh elements, and permits a reproducible result. These are made of grade 304 stainless steel with an aperture of $63 \mu\text{m}$ and a wire diameter of $36 \mu\text{m}$ which at its operating temperature of $900 \text{ }^\circ\text{C}$ resists oxidation for extensive periods, allowing experiments to be conducted in ambient air. Large currents through the elements can heat them to their operating temperature within 500 ms, which is small compared to particle burning times. Several methods have been tried in previous studies to regulate the temperature of wire mesh devices [15]. For this study the heating control method selected used was based upon the anticipated power demanded by the mesh to reach a specified temperature. On the centre line between the meshes are placed the sample holder and a 1 mm thick type K thermocouple (TC). This TC indicates the heat flux generated applied to the particle, rather than the particle's temperature, as it is not influenced by the heat released by of the volatile flame and char combustion of the particle. A program developed in LabVIEW was used to control the heating. The TC temperature was logged to ensure that the heating flux was consistent between runs, permitting particle-to-particle comparisons. The sample holder was made of the same wire mesh material as the heating elements, forming a rectangle of 3×6 mm with the sample over it. This design was found to be stable, with the sample particle normally remaining in situ (and at a constant distance from the meshes) throughout the experiments.

The high speed camera used in this study was a Phantom Miro eX4 with a zoom lens coupled to a 20 mm expansion tube to give image magnification. It was placed on the top of the apparatus with a glass to protect the lenses. The camera to particle distance was fixed so that a consistent optical magnification is achieved. The high speed video recording allow a good temporal resolution to be achieved. 500 frames per second were normally used for the recording exposure time of $3300 \mu\text{s}$ and resolution 128×128 pixels. A PC is used to retrieve the images

from the camera and all the videos were analysed using Phantom Control Camera. The recording was played back at real time and at reduced speed, allowing observation of much smaller particles and also phenomena that would be missed with a normal camera. The times for the respective phases in particle combustion were then accurately determined by processing the video image files and representative rankings of burning times were obtained.

3. Results and discussion

3.1. High speed video analysis

The recordings showed a sequential burning for the particles of both coal and biomass fuels. Figure 1 shows frames from a biomass particle on the main characteristic periods of combustion. Two steps of the combustion were identified as volatile combustion and char combustion. This is in agreement with previous works completed with other single particle devices [4,5,7,9,11,16,17,18].

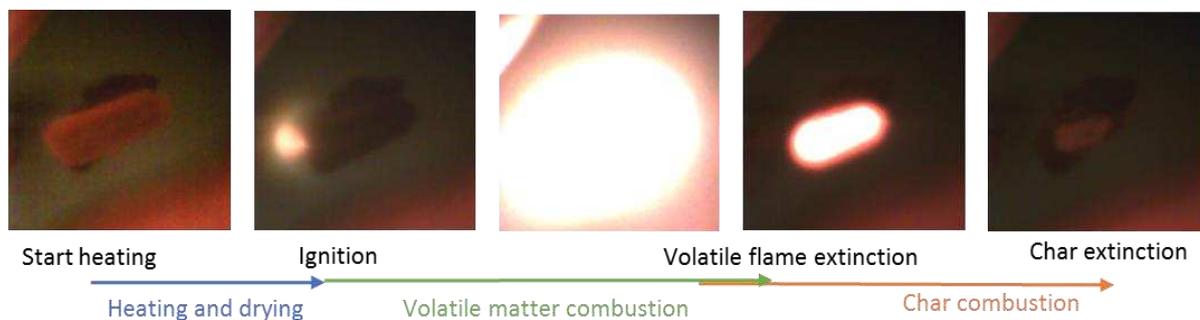


Figure 1. Sequential steps for the combustion of an WWP biomass particle.

Figure 2 shows particles of El Cerrejon coal and WWP biomass, a and b respectively, during the combustion. The percentage under the figure represents the proportion on the total burnout time since ignition. The biomass particle ignites very clearly on the gas phase (Figure 2b 0.0%), creating a big volatile flame during an extensive period of time, normally up to 40-50% of the total combustion time. Coal particle in Figure 2a also shows homogeneous ignition but a

significant difference in the combustion time of the volatile matter, normally up to 10-20 % of the total burnout time.

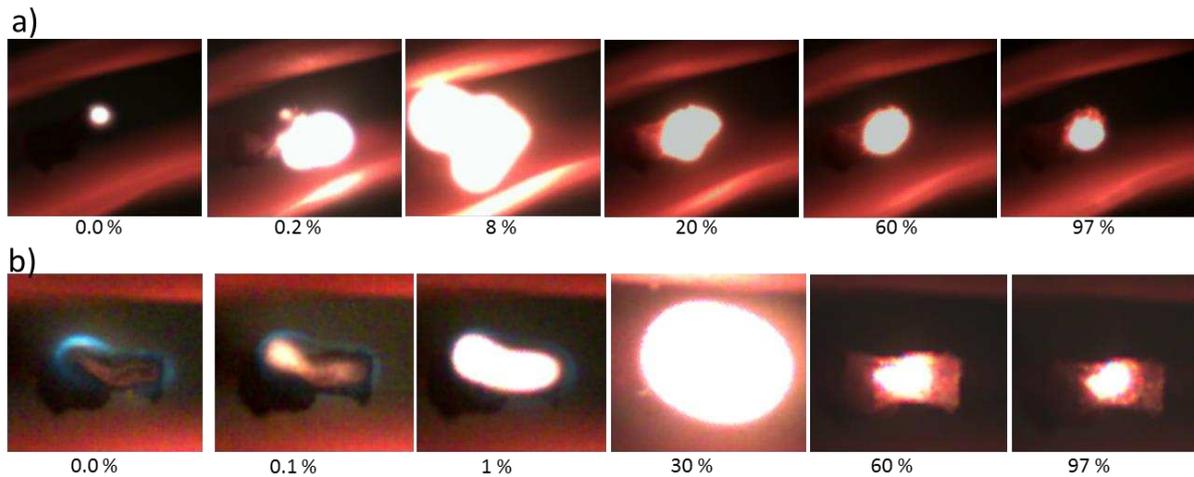


Figure 1. Frames from the combustion of the samples, a) coal b) white wood

Figure 3 shows some frames of this ignition phenomena with the flame surrounding the particle in the first second of the ignition. In most of the biomass samples the first sign of combustion is a flash flame close to the surface of the particle. This flame initially has a blue colour that after a few milliseconds gets bigger and also turns to bright yellow flame.

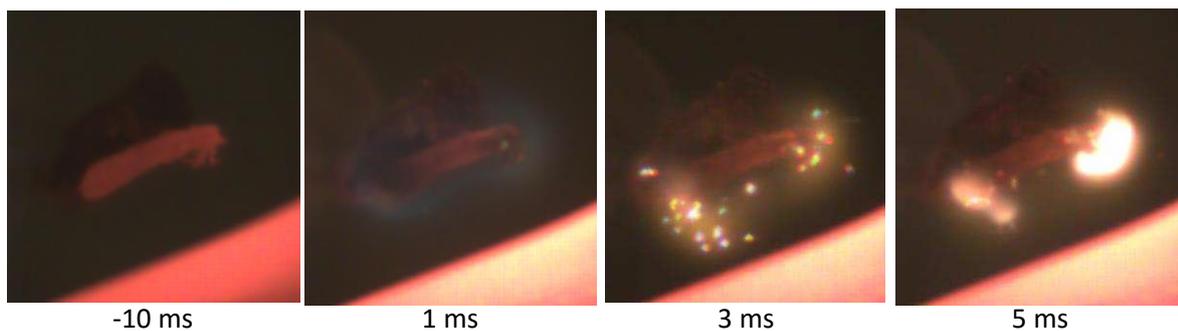


Figure 2. Frames from the ignition of the white wood biomass sample.

Coal also showed homogeneous ignition, most of the particles reveal a clear swelling leading to bigger char particles than the initial particle before ignition, as seen in Figure 3. This swelling is created by the high pressure reached inside the particle by the volatile compounds.

But the particle also needs to reach a plastic stage, where coal fluency allows the deformation of the particle. This is characteristic only of some high volatile bituminous coals. For a better observation of the swelling of the coal, some modifications were made in the support and camera. The mesh support was changed to an alumina plate to allow a better observation of the particle. The alumina plate absorbed much more energy than the mesh support, so it was only used for the purpose of swelling observation. An Edmund Optics cyan filter, which blocks light with wavelengths longer than 600nm, was applied to get a clear image of the particle. The sequence during the devolatilization of an El Cerrejon coal particle under this conditions can be observed in Figure 3.



Figure 3. Frames from the devolatilization and ignition step of El Cerrejón coal.

After ignition, the biomass volatile flame grew smoothly along the whole particle surface. According to this observation biomass volatile matter can flow through the porous particle [19] relatively easy while coal volatile matter released was delivered mainly as jets. The density and lower porosity of the coal particle at the beginning of the pyrolysis does not allow the volatiles to flow outside the particle [20]. When the pressure of the bubble inside the coal particle is enough to break the wall it reaches the surface and ignites. As a result of this and the large differences in volatile matter content, the times for the volatile matter combustion were much shorter for the coal than biomass. Therefore the pyrolysis is the dominant step for the half of total combustion time.

Compared with previous results [16] done with particles on the range of 90-125 μm there is a relatively long period of time when there is still a volatile flame visible but the char is already

burning. The size of the particle and the steady configuration of the particle over the support made the flame dragged by convection as a candle. This allows the oxygen to reach the surface of the particle and start the char burning as soon as the volatile flame shrinks enough.

The effect of mesh heating rate and final temperature affects the particle ignition delay, but once the particle ignites the heat coming from the combustion will be the main source of energy for the particle temperature. So small errors on the mesh temperature will have little effect during the combustion performance and burnout time. As Figure 1b shows, as the pyrolysis and combustion of volatiles progress, the shape of the biomass particle changes, sometimes the particle was bending over itself. The physical properties of the particle including porosity and surface area as well as the shape of the char particle differ from the original particle. The way these changes occur have rarely been observed due to the difficulties on the observation through the flame. The particle can be observed very clearly during the first frames of pyrolysis and ignition of the particle, however, once the volatile flame is developed it is not possible to see the aspect or shape of the particle until the volatile flame shrinks. Figure 4 represents frames at different stages of the combustion of the char plus the initial particle shown on the first image of the figure. The frame at 2% burnout shows the development of the volatile flame that has initially ignited at both extremes of the particle. At 50% of burnout it is observed that the char particle has changed its shape compared to the original particle, and it continues changing until the flame extinguishes.

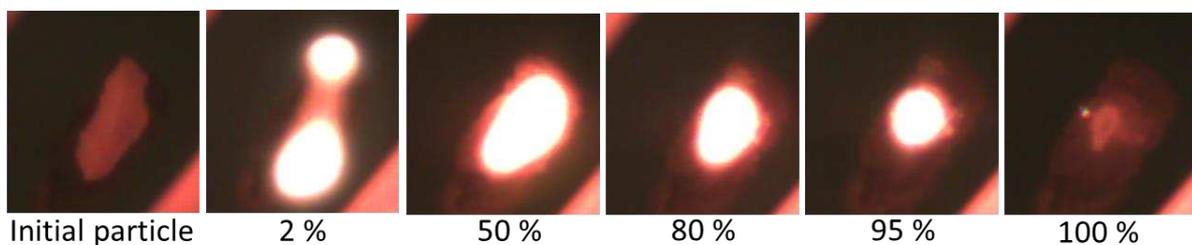


Figure 4. Frames from the combustion of white wood char and initial particle

The shape of the char was observed to be more rounded than that of the original particle. This is attributed to the surface tension of the particle that would be partially melted or softened at the temperatures reached during the combustion. According to these results, it can be deduced that the char particle is softened during the combustion allowing the particle to deform. The temperatures reached during the combustion of the char are much higher than during the volatile release [16]. Therefore the char particle becomes more rounded than the initial particle long and fibrous shape. The changing shape of the char with a constant evolution of the surface area has a great effect on the combustion rate. This creates a significant challenge for modelling of the combustion process of these fibrous biomass materials. The assumption of cylindrical shape particles will need to be revised to develop new models of particle structure, as biomass particle char normally ends with a very different shape than the initial raw biomass particle.

During the combustion of the char it was observed that the shrinkage of the particle was not the same in all directions of the particle. Long particles with fibrous shape are normally ignited at the end of the long edge of the particle and the flame then moves to the centre of the particle creating the large flame that is dragged by convection. During the combustion of the char similar trends could be observed. Initially, signs of particle consumption were observed at the extremes of the long axis. However the combustion is taking place all over the surface of the particle and is generally expected to affect the whole particle external structure. So it was expected that there would be a continuous reduction in the size of the particle at the same rate in all axes. Observed evolution of the char particle has been completely different. Very little shrinkage was observed along the short edge, on the contrary the particle seems to be bending from the extremes of the long axis towards the centre of the particle while burning.

The morphologies obtained showed evidences of being melted as some coals do. This is in agreement with Gil et al. [19] observations on chars obtained in a drop tube at high temperature. The chemical composition of both chars is also different. Both carbonaceous materials are

evolving towards a carbon rich material during pyrolysis, but the chemical composition of coal and chars is very complex. The compounds that form the biomass char are lighter hydrocarbons than those on the coal, consistent with the initial biomass composition [21]. This effect of char softening due to partial fusion is more clearly observed at the last step of the char combustion. Attempts of measuring the char temperature of fine particles in the past, were made by Riaza et al. [16], however the signals couldn't give the whole temperature history during char combustion. Only peak of maximum temperature were obtained, and those were estimated on the range of 1750 -1800 °C for the woody biomass particles of 75- 150 µm in air. This temperature is mainly produced due to the heat coming from the combustion. Additionally the furnace wall temperature was lower. It is likely that the char particle at that temperature transit to a softening due to the partial fusion of some of the compounds that form the char. The char particle becomes more round as an effect of the surface tension. The surface area of the char may be affected by these changes, leading to a progressive decrease on the specific surface area along the devolatilization and combustion. As char combustion is a heterogeneous reaction that takes place on the surface, this phenomena is influencing the combustion rate.

Mineral mater is transported during the combustion of the char. It has been observed in other studies [19] using SEM and XRF [21] that the mineral particulate matter is normally disperse over the particle. As the particle is consumed the fine ash particles become to be on the surface of the particle and as the particle shrinks they come together creating weak ash structures that were observed after the char combustion ends. The temperature at the particle could be enough for ash melting and it is also likely that on an industrial boiler some of this fine ash particles are dragged by the air and turbulence creating a range of fine ash particles [22].

3.2. Burnout times comparison

All particles were weighed to provide data needed to attempt to establish empirical relationships between particles weight and size range and its burnout time. The burnout time

for each particle could be measured from the video. These burnout times cannot be directly transposed to real conditions burnout times, as the heat transfer and combustion conditions are different, but it can be a way to compare among samples. Tendency lines on particle mass versus burnout times were obtained. The number of experiments done was 50 for coal particles and 104 for biomass particles. Particle weight vs burnout time for each particle and the tendency line is plotted in Figure 5.

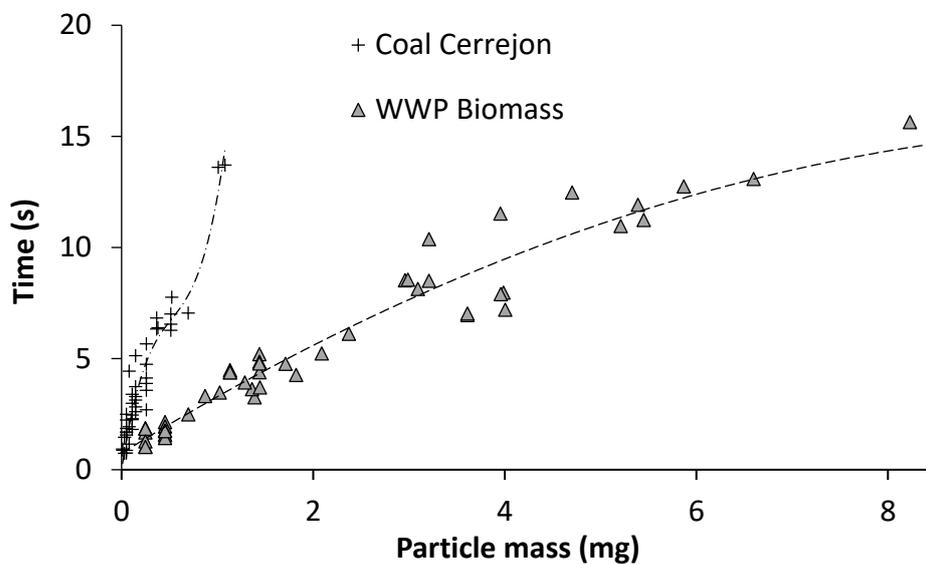


Figure 5. Burnout time of the particles of different weight.

The large increase tendency of coal burnout time with the increment of particle weight is also reflected in the literature and reports based on power plants operation. This reflects the great importance of the milling process and particle size distribution for an efficient burnout.

The aspect ratio defined as the length on major axis divided by length on minor axis of the biomass WWP in the range of sizes used was 5.7 ± 2 . The variability on the aspect ratio of the woody biomass particles makes the relationship between particle cut size and particle mass very variable. As a result, it is difficult to predict accurately a biomass particle mass for a given particle cut size. For very small particles the weight of the particle can have a considerable error. The deviation of the trend is large for some of the particles also because the heterogeneity

of biomass particles composition. Therefore this relationship needs to be taken with its limitations. As a first approximation to this relationship between particle size distribution it can be said that Coal particles in the range of 300-355 μm had an average weight of 31.3 mg, it can be found in the literature that around that size range would be the maximum for a complete burnout. The coal particle distribution above that size could lead to uncompleted burning. The burnout time for this range was 1.5 s excluding heating and drying. The equivalent biomass mass for the same burnout time would be 1,370 mg, which will be on mainly on the range size of 700 - 1120 μm . The next size range used, 355-425 μm , had an average weight of 50.9 mg and an average burnout time of 2.3s. Similar estimations can be done for the biomass equivalent particle that would be 2,230 mg that would be on the mean distribution of the particles between 1–1.4 mm. Further research is needed to establish a correlation strong enough to have a proper direct relationship on biomass particle sizes, mass and burnout time. And then also establish a size range that would be comparable in burnout time with pulverized coal sizes for an efficient burnout.

4. Conclusions

A high speed camera coupled to a single particle apparatus was optimized to reveal new data of combustion behaviour of El Cerrejón coal and white wood pellets biomass. Both fuels presented a very clear sequential step combustion, however the differences on chemical and physical properties led to differences in burning behaviour. Ignition and combustion of biomass volatiles was smooth with progressive growing flame, while coal released the volatile as jets. Ignition of char took place as soon as the volatile flame did not cover all of the particle surface. For the biomass particles the ignition of both volatile flame and char, was observed in the tips of the particle. The pyrolysis and combustion of volatile matter played an important role for the biomass, taking up to 50% of the burnout time. Char heterogeneous combustion reactivity

is the dominant mechanism for the overall coal burnout. The coal studied presented a significant swelling during the pyrolysis step. Biomass did not show swelling but a clear deformation of the particle was observed. The softening of the biomass during pyrolysis made the particle change to a more rounded shape and bend over itself. During the biomass char combustion, the partial melting of the particle and surface tension of the particle pulls its mass together becoming a more spherical shape with a change of the surface area of the char. Due to higher volatile content and reactivity, biomass particles can have a larger size than coal for the same burnout times. Coal particles in the range of 300-355 μm had similar burnout times than 700 - 1120 μm biomass for the experimental setup and conditions used.

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Supplementary material

Supplementary material associated with this article can be found in the online version.

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