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Ignition and combustion of single particles of coal and biomass

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A B S T R A C T

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 is used as a heating element to heat the particle by radiation while optical access allows 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, devolatilization 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 in 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 even for the initial fibrous shape of the woody biomass particles.

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 make progress in the development of more efficient and cleaner combustion. Detailed investigation of 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 management and more sustainable transport to all scales of consumers [2]. This also facilitates reliable performance of the combustion with less variable 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 [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

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combustion of the particles, while bituminous coal shows a volatile flame prior to char combustion. The main different single particle setups, summarized by Marek et al. [3], have been used to provide proper descriptions of the combustion process. The implementation of the techniques has provided more data including particle temperature [6] or particle aspect ratio during the combustion [7]. More recently single particle studies have considered combustion in oxy-fuel atmospheres, including Khatami et al. [4] 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 furnace 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 O_2/CO_2 atmospheres, producing a delay in the order of 10 ms 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 earlier volatile release 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. The combustion reactions are still the main conductor of the flame and burnout though.

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]. Mason et al. [11] performed 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 Lu et al. [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 combustion performance is needed to establish the milling requirements for 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 at least 80% below 75 μm [14]. 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 examined a range of woody biomass particle sizes in order to establish which size would have the same burnout time as the maximum size of coal particles typically burned in utility boilers, i.e., 300 μm. The combustion test data can inform 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 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), which 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, high volatile matter content and a calorific value much lower than the coal. Proximate and ultimate analyses are given in Table 1.

Each sample was milled, dried and sieved to different ranges of sizes. The particle sizes used were between 3 mm and 610 μm for biomass, and 1 mm to 300 μm for the coal sample. The minimum size for coal particles was decided based on previous preliminary experiments. The difficulties of handling plus the errors on weight and ignition time detection were reduced by using sizes above 300 μm. Samples were dried in an oven at 115 °C for 2 h to remove any moisture. Each particle was weighed before experiment using weighing balance six digits balance Sartorious Secura 225.

2.2. Experimental device

The wire mesh apparatus used in this work allows a stationery particle sample to be recorded as it burns with high speed video camera. The single particle apparatus is substantially the experimental device described in Flower et al. [9], it only differs in the camera and heating control system used. 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 μm and a wire diameter of 36 μm which at its operating temperature of 900 °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. The sample holder and a 1 mm thick type K thermocouple (TC) are placed on the centre line between the meshes. This TC indicates the heat flux generated and applied to the particle, rather than the particle's temperature, as it is not influenced by the heat released by the volatile flame and char combustion of the particle. A program developed in LabVIEW was used to control the heating. The

Table 1
Proximate and ultimate analysis of the samples used.

	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

TC temperature was logged to ensure that the heat 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 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. Small errors on the mesh temperature will, therefore, have little effect during the combustion performance and burnout time.

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 was achieved. The high speed video recording allowed a good temporal resolution to be achieved. 500 frames per second were normally used for the recording exposure time of 3300 μs and resolution 128 × 128 pixels. A PC was 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. The multiple range test was used to establish whether differences between mean burnout time results for different weight of particles where statistically significant using Statgraphics Plus software.

3. Results and discussion

3.1. High speed video analysis

The recordings showed a sequential burning for the particles of both bituminous coal and biomass fuels. Fig. 1 shows frames from a biomass particle during 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 [4,5,7,9,11,16–18].

Fig. 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 (Fig. 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 Fig. 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.

Fig. 3 shows some frames of the 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 into a bright yellow flame.

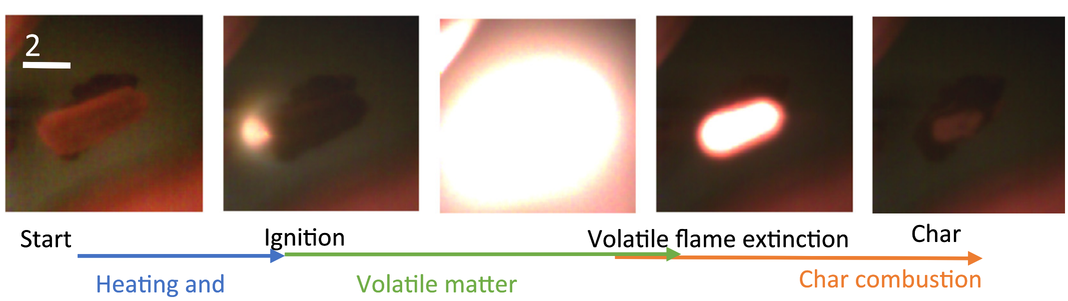

Fig. 1. Sequential steps for the combustion of an WWP biomass particle.

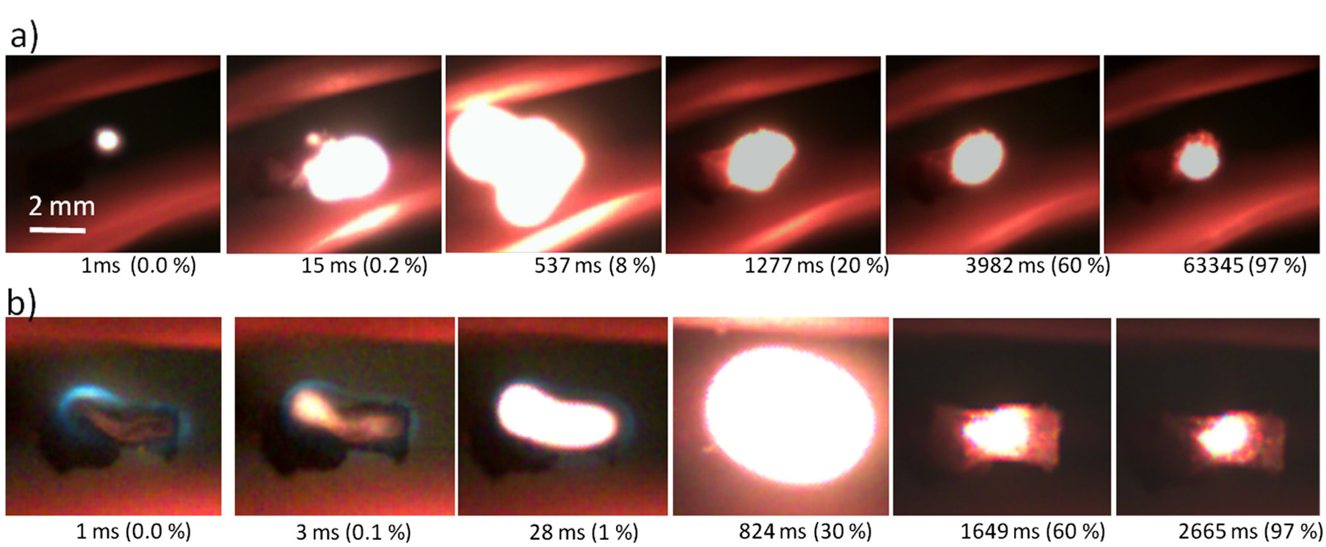

Fig. 2. Frames from the combustion of the samples, a) coal b) white wood. Times below refers to times from ignition and percentage of total burnout time.

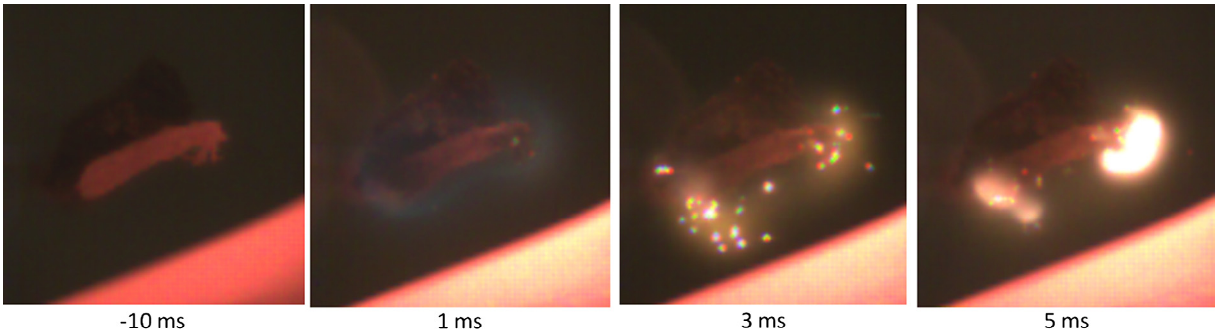

Fig. 3. Frames from the ignition of the white wood biomass sample. Times below refers to times from ignition.

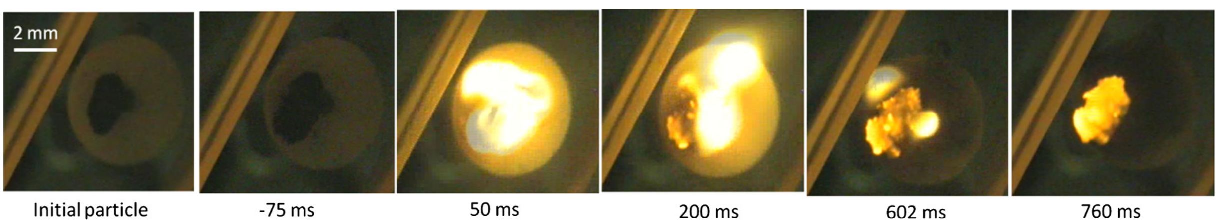

Fig. 4. Frames from the devolatilization and ignition step of El Cerrejón coal. Times below refers to times from ignition.

The coal also showed homogeneous ignition, with most of the particles having a clear swelling leading to bigger char particles than the initial particle before ignition, as seen in Fig. 4. 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. Additionally, an Edmund Optics cyan filter, which blocks light with wavelengths longer than 600 nm, was applied to get a clear image of the particle. The sequence during the devolatilization of an El Cerrejon coal particle under these conditions can be observed in Fig. 4.

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 easily 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 out of 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 coal for half of total combustion time.

Compared with previous results [16] with coal 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 meant that the flame was 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.

As Fig. 1b shows, as the pyrolysis and combustion of volatiles progress, the shape of the biomass particle changes. For example, 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 has rarely been observed due to the difficulty of making accurate observations 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. Fig. 5 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% of total time burnout shows the development of the volatile flame that has initially ignited at both extremes of the particle. At

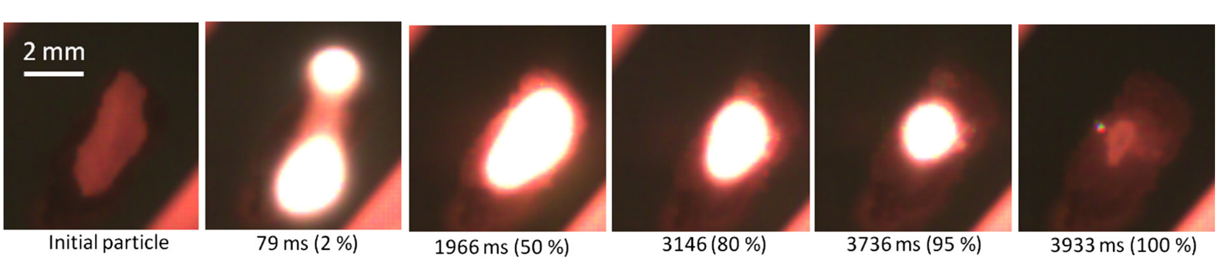

Fig. 5. Frames from the combustion of white wood char and initial particle.

50% of total time 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.

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 WWP 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 can 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 evidence of being melted as some coals do. This is in agreement with Gil et al. [19] observations on chars obtained in a drop tube furnace 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. Char surface temperatures of fine biomass and coal particles (75–150 μm) were measured in the past by Riaza et al. [16] throughout their entire burnout times, see Fig. 9 therein. At a furnace temperature of 1400 K, the peak char temperatures of woody biomass particles, burning in air, averaged between 1750 and 1800 K, see Fig. 8 therein. It is likely that the char particle at these temperatures will 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 as devolatilization and combustion progresses. As char combustion is a heterogeneous reaction that takes place on the surface, this phenomena is influencing the combustion rate.

Finally, mineral matter is transported during the combustion of the biomass char. It has been observed in other studies using SEM and XRF [19,21] that the mineral particulate matter is normally disperse over the particle. As the particle is consumed the fine ash particles are observed 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 in an industrial boiler some of these 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 particle weight and size range and 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 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 Fig. 6.

The relationship between weight and burnout time results for coal and biomass particles on the size ranges of 600–710 μm and 710–1000 μm were used for a statistical analysis. A *t*-test to compare the means of the two samples could not find significant differences between the weight of the particles. However statistically significant differences were found comparing the burnout times. Mean burnout time for ranges of 600–710 μm and 710 – 1000 μm for coal were 4.1 s ± 1 s and 6.6 s ± 0.9 s respectively, and 1.5 s ± 0.4 s and 1.7 s ± 0.5 s for the biomass. The t-tests found there is a statistically significant difference between the means of the two samples at the 95% confidence level, concluding that biomass has shorter burnout times with P-values below 0.05. That is not surprising due to the different observed behaviour and reactivity of the fuels.

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.

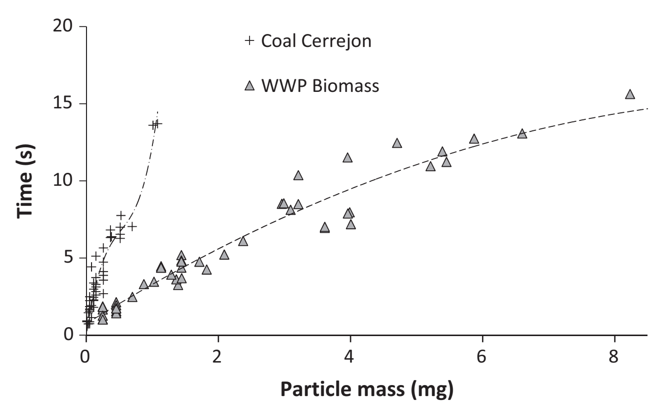

Fig. 6. Total burnout time of the particles of different weight.

Nevertheless, as a first approximation, it can be said that coal particles in the range of 300–355 μm had an average weight of 0.0313 mg. The literature suggests that this size range is around the maximum where complete burnout would be expected for a pulverized fuel boiler. The coal particle distribution above that size could lead to uncompleted burning. The mean burnout time for this range was 1.5 ± 0.4 s excluding heating and drying. The equivalent biomass mass for the same burnout time would be 0.36 mg, which is typical of biomass in the size range of 600–1000 μm. The next coal size range used, 355–425 μm, had an average weight of 0.051 mg and an average burnout time of 2.3 ± 0.4 s. The biomass equivalent particle mass for similar burnout time would be 0.6 mg which is typical of the particles between 710 and 1120 μm. However, further research is needed to establish a general correlation strong enough to characterise a proper direct relationship between biomass particle size distributions, mass and burnout time. This could then be used to establish a size distribution 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 a progressive growing flame, while coal released the volatile as jets. Ignition of biomass char took place on the tips of the particle once the volatile flame was not covering all 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 leading to a more spherical shape with an associated 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 (typical of the maximum size for complete burnout in a utility boiler) had similar burnout times to 600–1000 μm biomass for the experimental setup and conditions used.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.fuel.2017.04.011. Further data associated with this work can be accessed through the record of this publication available in the University of Edinburgh Current Research Information System (PURE) at www.pure.ed.ac.uk.

References

[1] Saeed M, Andrews G, Phylaktou H, Gibbs B. Global kinetics of the rate of volatile release from biomasses in comparison to coal. Fuel 2016;181:347–57.
[2] The European Biomass Association (AEBIOM). Statistical Report 2015. Retrieved September 28, 2016 from: http://www.aebiom.org/library/statistical-reports/statistical-report-2015/.
[3] Marek E, Stańczyk K. Case studies investigating single coal particle ignition and combustion. J Sustain Mining 2013;12:17–31.
[4] Khatami R, Stivers C, Joshi K, Levendis Y, Sarofim A. Combustion behavior of single particles from three different coal ranks and from sugar cane bagasse in O2/N2 and O2/CO2 atmospheres. Combust Flame 2012;159:1253–71.
[5] Riaza J, Khatami R, Levendis YA, Álvarez L, Gil MV, Pevida C, et al. Single particle ignition and combustion of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions. Combust Flame 2014;161:1096–108.
[6] Khatami R, Levendis Y. On the deduction of single coal particle combustion temperature from three-color optical pyrometry. Combust Flame 2011;158:1822–36.
[7] Lee H, Choi S. An observation of combustion behavior of a single coal particle entrained into hot gas flow. Combust Flame 2015;162:2610–20.
[8] Gubba SR, Ma L, Pourkashanian M, Williams A. Influence of particle shape and internal thermal gradients of biomass particles on pulverised coal/biomass co-fired flames. Fuel Process Technol 2011;92:2185–95.
[9] Flower M, Gibbins J. A radiant heating wire mesh single-particle biomass combustion apparatus. Fuel 2009;88:2418–27.
[10] Flower M. Combustion of single biomass particles in a heated wire mesh apparatus with video based measurements. PhD Thesis 2010, Mechanical Engineering Department, Imperial College London, South Kensington, UK.
[11] Mason PE, Darvell LI, Jones JM, Pourkashanian M, Williams A. Single particle flame-combustion studies on solid biomass fuels. Fuel 2015;151:21–30.
[12] Brix J, Jensen P, Jensen A. Modeling char conversion under suspension fired conditions in O 2/N2 and O2/CO2 atmospheres. Fuel 2011;90:2224–39.
[13] Lu H, Ip E, Scott J, Foster P, Vickers M, Baxter L. Effects of particle shape and size on devolatilization of biomass particle. Fuel 2010;89:1156–68.
[14] Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers. IEA Clean Coal Centre 2016. ISBN: 978–92–9029–586-0.
[15] Man C, Gibbins J, Witkamp J, Zhang J. Coal characterisation for NOx prediction in air-staged combustion of pulverised coals. Fuel 2005;84:2190–5.
[16] Riaza J, Khatami R, Levendis YA, Álvarez L, Gil MV, Pevida C, et al. Combustion of single biomass particles in air and in oxy-fuel conditions. Biomass Bioenergy 2014;64:162–74.
[17] Marek E, Świątkowski B. Experimental studies of single particle combustion in air and different oxy-fuel atmospheres. Appl Therm Eng 2014;66:35–42.
[18] Yang YB, Sharifi VN, Swithenbank J, Ma L, Darvell LI, Jones JM, et al. Combustion of a single particle of biomass. Energy Fuels 2008;22:306–16.
[19] Gil MV, Riaza J, Álvarez L, Pevida C, Rubiera F. Biomass devolatilization at high temperature under N2 and CO2: Char morphology and reactivity. Energy 2015;91:655–62.
[20] Gil MV, Riaza J, Álvarez L, Pevida C, Pis JJ, Rubiera F. Oxy-fuel combustion kinetics and morphology of coal chars obtained in N2 and CO2 atmospheres in an entrained flow reactor. Appl Energy 2012;91:67–74.
[21] Xing P, Darvell L, Jones J, Mab L, Pourkashanian M, Williams A. Experimental and theoretical methods for evaluating ash properties of pine and El Cerrejon coal used in co-firing. Fuel 2016;183:39–54.
[22] Ruscio A, Kazanc F, Levendis Y. Comparison of fine ash emissions generated from biomass and coal combustion and valuation of predictive furnace deposition indices A review. J. Energy Eng. 2015;142.