



This is a repository copy of *Ignition and combustion of single particles of coal and biomass under O<sub>2</sub>/CO<sub>2</sub> atmospheres*.

White Rose Research Online URL for this paper:  
<http://eprints.whiterose.ac.uk/133055/>

Version: Published Version

---

**Proceedings Paper:**

Riaza, J., Ajmi, M., Gibbins, J. [orcid.org/0000-0003-0963-4555](https://orcid.org/0000-0003-0963-4555) et al. (1 more author) (2017) Ignition and combustion of single particles of coal and biomass under O<sub>2</sub>/CO<sub>2</sub> atmospheres. In: Energy Procedia. 13th International Conference on Greenhouse Gas Control Technologies, 14-18 Nov 2016, Lausanne, Switzerland. Elsevier , pp. 6067-6073.

<https://doi.org/10.1016/j.egypro.2017.03.1743>

---

**Reuse**

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial (CC BY-NC) licence. This licence allows you to remix, tweak, and build upon this work non-commercially, and any new works must also acknowledge the authors and be non-commercial. You don't have to license any derivative works on the same terms. More information and the full terms of the licence here:  
<https://creativecommons.org/licenses/>

**Takedown**

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



[eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk)  
<https://eprints.whiterose.ac.uk/>



13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

## Ignition and combustion of single particles of coal and biomass under O<sub>2</sub>/CO<sub>2</sub> atmospheres

Juan Riaza<sup>a\*</sup>, Muhammad Ajmi<sup>a</sup>, Jon Gibbins<sup>b</sup>, Hannah Chalmers<sup>a</sup>

*a Institute for Energy Systems, School of Engineering, University of Edinburgh,  
The King's Buildings, Mayfield Road, Edinburgh, EH93JL, Scotland, UK*

*b Department of Mechanical Engineering, University of Sheffield, Mappin Street, S13JD, Sheffield*

### Abstract

Biomass energy with carbon dioxide capture and storage (CCS) technologies like oxy-fuel is the only way to achieve net removal of CO<sub>2</sub> from the atmosphere in power generation. A single particle apparatus has been developed for rapid heating and combustion of individual fuel particles in air or O<sub>2</sub>/CO<sub>2</sub> atmospheres. 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. Four different biomass and a bituminous coal were used in air and 21, 30 and 40 % O<sub>2</sub> atmospheres with balance of CO<sub>2</sub>. High speed video image analysis showed differences in ignition and devolatilization behaviour. The influence of particle size and mass on burnout times was higher in the coal, while biomass particle size can have a greater range of sizes for the same burnout times. The 30%O<sub>2</sub> atmosphere was enough to have less burnout time than in air atmosphere for all the samples. 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 those that initially had a fibrous shape.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of GHGT-13.

*Keywords:* Oxyfuel, biomass, coal, single particle

### 1. Introduction

Biomass is being increasingly implemented as an energy source for electricity generation in modern biomass power plants and co-firing or to replace other fuels such as coal. The use of co-fired biomass in existing pulverized coal power plants requires only minor modifications compared to the construction of new biomass-only fired power plants. This makes co-firing biomass with coal an attractive option for making effective use of biomass energy. Co-firing of biomass with coal is also useful from the perspectives of maximising use of available resources, improving plant fuel flexibility and reducing cumulative CO<sub>2</sub> emissions to atmosphere. On the other hand, conventional power generation needs to reduce CO<sub>2</sub> emissions by applying CO<sub>2</sub> capture technology. Combining biomass combustion with carbon dioxide capture and storage (CCS) like oxy-fuel is a promising

\* Corresponding author. Tel.: +44(0)1316507444 ; fax. +44(0)1316506554.  
E-mail address: [juan.riaza@ed.ac.uk](mailto:juan.riaza@ed.ac.uk)

approach from power generation to achieve net removal of CO<sub>2</sub> from the atmosphere. CO<sub>2</sub> removed from the atmosphere as biomass grows can be permanently stored away from the atmosphere providing the potential for ‘negative’ emissions with oxy-biomass Co-firing technology under oxy-fuel conditions has to overcome some technical complications due to the differences in the fuel properties and behaviour in the combustion.

Oxy-fuel operation is based on replacing the nitrogen (N<sub>2</sub>) that would be present in air combustion with CO<sub>2</sub> that is recycled from the combustion flue gas [1], with the oxygen (O<sub>2</sub>) being added at relatively high purity from an air separation unit. Whereas in air firing the oxygen content is a constant 21%v/v, in oxy-fuel firing the concentration can be controlled at essentially any desired value. In general, however, the aim will be to obtain similar performance in oxy-fuel plant as in air-fired plant. Combustion of biomass in the boiler in O<sub>2</sub>/CO<sub>2</sub> atmospheres would ideally also occur in a similar manner to air combustion, without excessive ignition delays as the fuel enters the boiler but also without overly intense combustion near the burner tips. The CO<sub>2</sub> recycle in oxy-fuel combustion increases the partial pressure of carbon dioxide downstream for ease of treatment at compression and purification unit before transport and sequestration [1] but its increased heat capacity may also tend to delay the pulverized fuel ignition if the O<sub>2</sub> content is not raised to compensate.

Single particle combustion experimental setups have been an effective approach to understand the combustion phenomena and the variables that may affect the combustion of different fuels under different conditions [2]. Under very controlled conditions single particle experiments have been able to observe tendencies that have been replicated on much larger scale. The results are also good to develop models that then are able to predict with more accuracy the flame development and combustion kinetics. Study the effect of the particle size distribution and shape [4,5] have demonstrated its influence on the combustion performance. As biomass characteristics differs from coal in ignition temperatures, behaviour, and burnout times, single particle combustion have also been done to study this differences [6,7,8,9]. The measurement of particle temperature [8] or particle aspect ratio during the combustion [9] have been good contributions on combustion understanding. Recent studies have [7] pointed out differences in single particle combustion of fuels in different oxy-fuel atmospheres. 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<sub>2</sub>/CO<sub>2</sub> atmospheres, producing a delay in the ignition also observed in studies in other experimental devices [10].

Fuel particle distribution has a large significance in the combustion and therefore in power plant operation [11]. Coal fuel is normally milled to sizes below 300 µm with most of the fuel below 75 µm. The particles above 300 µm are likely to produce carbon in ash, which is a problem for power plant operation and efficiency. Research is needed to improve the knowledge available in biomass and coal combustion and milling requirements for oxy-fuel technology to progress in the development of more efficient and cleaner power generation. Detailed investigation in the ignition and combustion of the diversity of fuels in oxy-fuel atmospheres is needed to establish the differences that may affect the design of burners and furnace performance.

The objective of the present study was to observe the differences in the ignition and combustion behaviour for particles of fuels in O<sub>2</sub>/CO<sub>2</sub> atmospheres 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 compare the maximum particle size for each fuel that would have the same burnout as a given coal particle. 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 in the different oxy-fuel atmospheres.

## 2. Materials and methodology

### 2.1. Fuel samples used

The selection of the fuels was based on their wide use in the UK and worldwide. One coal “El Cerrejón” (CC) was used, this coal is imported from Colombia and is a high volatile bituminous coal. Three different biomass samples were used, white wood pellet (WW), olive waste (OW) and steam exploded pellet (SP). The SP is a biomass that has been torrefacted in a steam environment and has been supplied as pellets. WW biomass 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 of the fuels 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 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.

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

	El Cerrejón (CE)	White wood (WW)	Olive waste (OW)	Steam exploded Pellet (SP)
moisture content (% wt)	5.5	7.8	5.9	7.2
ash content dry (% wt)	1.2	1	7.6	4.2
volatile content daf (% wt)	40.1	91.8	80.1	79.4
fixed carbon daf (% wt)	59.9	8.2	19.9	20.6
GCV (dry) (MJ/kg)	32.7	17.75	20.1	20
Elemental daf (% wt)				
C	73	51.5	52.8	52.7
H	5.2	3.1	6.5	5.8
O	19.6	44.7	39.1	41.2
N	2.2	0.6	1.6	0.2

## 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 has been developed based on a previous experimental device explained in Flowers et al. [12]. 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  $40 \times 40$  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  $900^\circ\text{C}$  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. The heating elements and particle are inside a reactor chamber. Once the particle is placed over the support, the reactor is closed to proceed to create the desired atmosphere. A vacuum pump is used to create  $-850$  mbar vacuum, then the chamber is filled with the  $\text{O}_2/\text{CO}_2$  mixture using mass flow controllers until the pressure is back to atmospheric. The atmospheres used were Air, and 21, 30 and 40 % $\text{O}_2$  with balance to  $\text{CO}_2$ .

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  $128 \times 128$  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 under air conditions done for CE coal and WW biomass, showed a sequential burning for the particles of both coal and biomass fuels. Figure 1 shows frames from a WW biomass particle on the main characteristic periods of combustion.

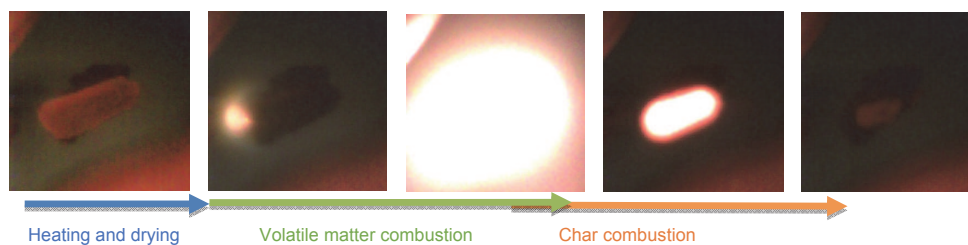
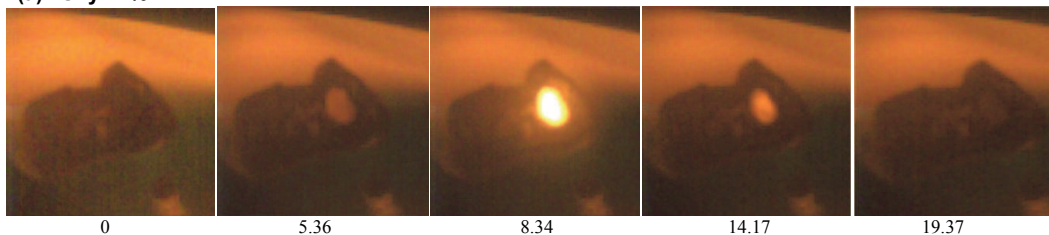


Figure 1. Sequential steps for the combustion of a WW biomass particle in air.

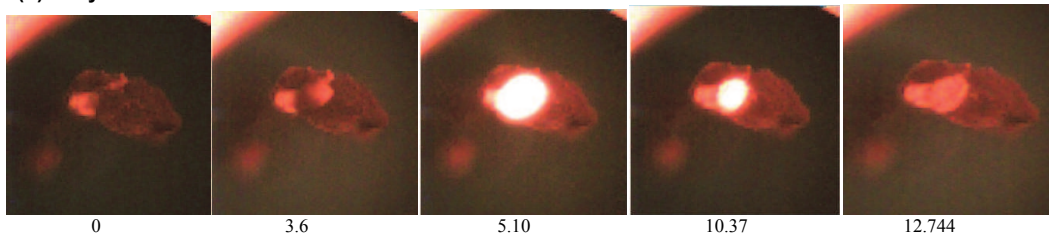
Two steps of the combustion were identified as volatile combustion and char combustion. This is in agreement with previous works completed with other single particle devices [6,7,9,12-16]. However the recordings under the different oxy-fuel atmospheres showed much more diverse ignition behaviour. Some particles at 21% $\text{O}_2$  / 79% $\text{CO}_2$  ignited directly on the surface and had a heterogeneous combustion. The heating rate in this device is not as high as in a drop tube, so it could happen that the

pyrolysis gas are released without ignition and then ignition take place on the surface of the char. This effect can be attributed to the different thermal properties of the  $\text{CO}_2$ . As in agreement with previous studies, the ignition delay can be increased due to the higher heat capacity of the  $\text{CO}_2$ . The difference between particle and surrounding gas temperature could be enough to absorb the energy reducing the pyrolysis gas under their flash temperature. On other cases, the particle start with a hot point of ignition on the surface of the particle that makes the pyrolysis gas to ignite. This has been described as hetero-homogeneous ignition in studies done by Essenhigh et al. [17]. Figure 2 shows frames from the high speed video obtained in the different oxy-fuel atmospheres. The time below the image is the time from the start of the heating of the mesh in seconds.

(a) Oxy 21% - CE



(b) Oxy 30% - CE



(c) Oxy 40% - CE

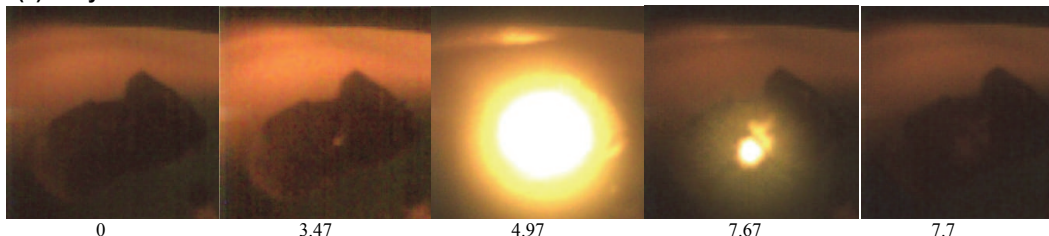


Figure 2. Coal combustion at 21%, 30% and 40%  $\text{O}_2$  concentration with balance of  $\text{CO}_2$ .

Coal particles reveal a clear swelling leading to bigger char particles than the initial particle before ignition, as seen in Figure 2. 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. Figure 3 represents frames at different stages of the combustion of the biomass fuels in the different atmospheres tried.

As Figure 3 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. According to these observation, 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 burning [14] and are increased with the higher amount of oxygen in the oxy-fuel atmospheres. The char particle becomes more rounded than the initial particle due to the surface tension of the particle that would be partially melted. The changing shape of the char with a constant evolution of the surface area has a great effect on the combustion rate. The morphologies changes observed can be interpreted as an evidence of being melted as previously observed by Gil et al. [18] in chars obtained in a high temperature drop tube.

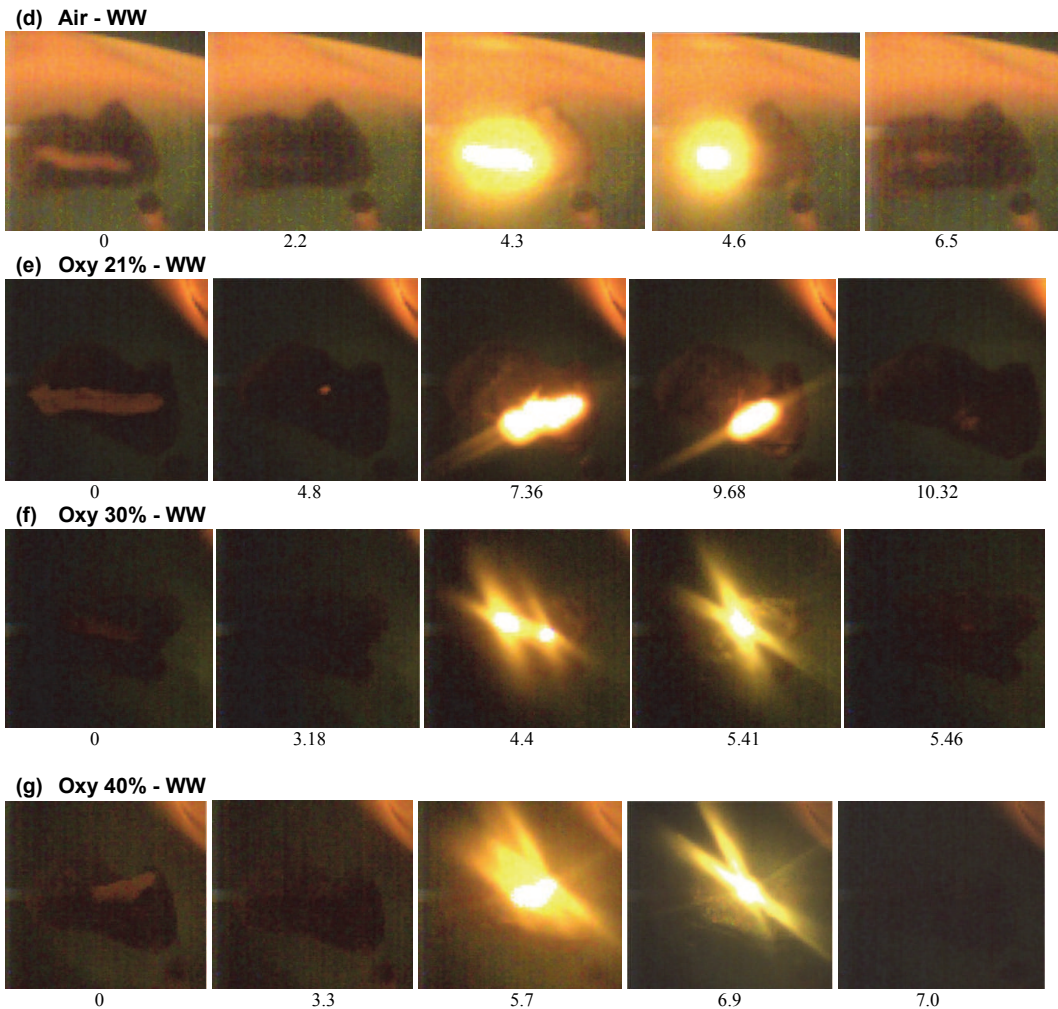


Figure 3. Frames from the combustion of WW biomass on the different atmospheres.

The char melting is more clearly observed by the end of the particle combustion. As combustion progress the particle is heated reaching a maximum temperature at the last steps [14]. When the oxygen concentration in the atmosphere increases, the energy is more quickly released as the combustion kinetics are faster. So melting and shape changes occur faster for the higher oxygen concentration atmospheres. As a result, char particle becomes more round due to the surface tension and changes in surface area are expected. As char combustion is a heterogeneous reaction that takes place on the surface, more research is needed to detailed describe the progressive decrease on the specific surface area of the particle along the devolatilization and combustion steps and how this phenomena is influencing the combustion rate.

### 1.1. 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 between 10 and 20 for sample in each condition. In order to have a better comparison among the fuels burnout on the different atmospheres, a value of burnout time for a particle of 0.8 mg was calculated from the tendency line. The values obtained are plotted in Figure 4.

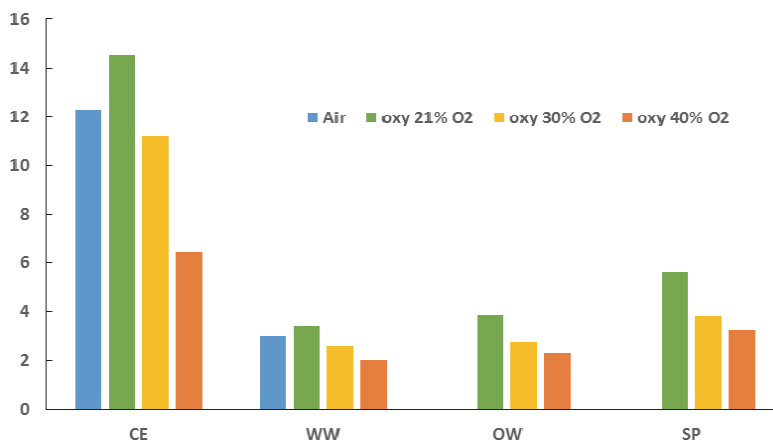


Figure 4. Burnout time of the different fuels for a 1 mg particle on different oxy-fuel atmospheres.

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. Due to higher volatile content and reactivity, biomass particles can have a larger size than coal for the same burnout times.

The most reactive biomass with the shortest burnout time in all the atmospheres was WW, followed by OW and SP. The influence of the atmosphere was noticeable in all the fuels, with same tendencies as the atmosphere changed. However the effect on the coal is much greater than in the biomass fuels tried. This can be explained by the importance of the pyrolysis step in the biomass fuels. The pyrolysis kinetics plays an important role on the overall combustion process, being practically independent from the oxygen content, therefore the O<sub>2</sub> concentration has more influence in the burnout time for the lower volatile matter content fuels.

## 2. Conclusions

A high speed camera coupled to a single particle apparatus was optimized to reveal new data of combustion behavior of El Correjón coal and various biomass under air and O<sub>2</sub>/CO<sub>2</sub> atmospheres. The fuels presented a very clear sequential step combustion in air, however the ignition in oxy-fuel atmospheres tend to be heterogeneous in the 21% O<sub>2</sub> atmosphere and homogeneous in 40% O<sub>2</sub> atmosphere. The differences on chemical and physical properties also led to differences in burning behavior. Ignition and combustion of biomass volatiles was smooth with progressive growing flame, while coal released the volatile as jets. The coal studied presented a significant swelling during the pyrolysis step. Biomass fuels showed a clear deformation of the particle was observed. 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. This effect was observed regardless the atmosphere but was more pronounced for the high oxygen content atmosphere.

## Acknowledgements

The scientific work has been supported by the BIO-CAP-UK project and the Future Conventional Power research consortium supported by The Engineering and Physical Sciences Research Council (EPSRC) ([www.epsrc.ac.uk](http://www.epsrc.ac.uk)) and UK CCS Research Centre ([www.ukccsrc.ac.uk](http://www.ukccsrc.ac.uk)).

## References

- [1] Gale J. et al (2011) Oxy-fuel Combustion Technology Working Toward Demonstration and Commercialisation, International Journal of Greenhouse Gas Control Volume 5, Supplement 1 (ISSN 1750-5836)
- [2] Marek E, Stańczyk K. Case studies investigating single coal particle ignition and combustion. *Journal of Sustainable Mining* 2013;12:17–31.
- [3] Brix J, Jensen P, Jensen A. Modeling char conversion under suspension fired conditions in O<sub>2</sub>/N<sub>2</sub> and O<sub>2</sub>/CO<sub>2</sub> atmospheres. *Fuel* 2011;90:2224–2239.
- [4] 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.
- [5] 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;89:1156–1168.
- [6] Khatami R, Stivers C. Combustion behavior of single particles from three different coal ranks and from sugar cane bagasse in O<sub>2</sub>/N<sub>2</sub> and O<sub>2</sub>/CO<sub>2</sub> atmospheres. *Combust Flame* 2012;159:1253–71.

- [7] 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. *Combustion Flame* 2014;161:1096–1108.
- [8] Khatami R, Levendis Y. On the deduction of single coal particle combustion temperature from three-color optical pyrometry. *Combustion Flame* 2011;158:1822–1836.
- [9] Lee H, Choi S. An observation of combustion behavior of a single coal particle entrained into hot gas flow. *Combustion Flame* 2015;162:2610–2620.
- [10] Riaza J, Gil MV, Álvarez L, Pevida C, Pis JJ, Rubiera F. Oxy-fuel combustion of coal and biomass blends. *Energy* 2012;41:429–435
- [11] Wiatros-Motyka M. Optimising fuel flow in pulverised coal and biomass-fired boilers. IEA Clean Coal Centre 2016. ISBN: 978–92–9029–586-0.
- [12] Flower M, Gibbins J. A radiant heating wire mesh single-particle biomass combustion apparatus. *Fuel* 2009;88:2418–27.
- [13] Mason PE, Darvell LI, Jones JM, Pourkashanian M, Williams A. Single particle flame-combustion studies on solid biomass fuels. *Fuel* 2015;151:21–30.
- [14] 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;64:162–174.
- [15] Marek E, Świątkowski B. Experimental studies of single particle combustion in air and different oxy-fuel atmospheres. *Applied Thermal Engineering* 2014;66:35–42.
- [16] 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.
- [17] Essenhigh R, Misra M, Shaw D. Ignition of coal particles: A review. *Combustion and Flame* 1989;77:3–30
- [18] Gil MV, Riaza J, Álvarez L, Pevida C, Rubiera F. Biomass devolatilization at high temperature under N<sub>2</sub> and CO<sub>2</sub>: Char morphology and reactivity. *Energy* 2015;91:655–662.