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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 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