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Single particle flame-combustion studies on solid biomass fuels

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HIGHLIGHTS

- We describe an experiment on the combustion behaviour of single particles of solid biomass.
- The experiment measures: ignition delay; volatile flame duration; char burn duration.
- Results are presented for 3 materials: pine; eucalyptus; willow.
- Empirical relationships between particle size and combustion behaviour are derived.
- Modelling shows that the empirical relationships are valid.

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ABSTRACT

Combustion of solid biomass in large scale power generation has been recognized as a key technology for the transition to a decarbonized electricity sector in the UK by 2050. Much of the near-term forecast capacity is likely to be by the conversion of existing coal-fired pulverized fuel plant (DECC, 2012). In such applications, it will be necessary to ensure that the combustion behaviour of the solid biomass fuels is engineered to match, as far as practical, that of the original plant design. While biomass feedstock characteristics vary considerably, one controllable variable for pulverized fuel is the size of the particles.

Useful modelling for adaptation and design of boiler plant can be improved with more detailed measurement of the real behaviour of individual particles of the varying fuels. Typical power plant biomass fuels including pine, eucalyptus and willow with particle sizes ranging from up to 3 mm (Van Loo and Koppejan, 2008) and with differing moisture content and aspect ratios were selected for study. Single particles were supported in a water-cooled cover and then exposed above a flame, simulating biomass combustion in a furnace. Measurements of ignition delay, volatile burning time and char burn-out time were undertaken using high speed image capture. Temperatures of the surrounding environment and near to the particle surface were measured with thermocouples and thermometric imaging. Thermogravimetric measurements on separate samples complement the single particle measurements as a means of verifying the demarcation between the different stages of combustion and providing kinetic data.

Analysis of the data identified correlations between the biomass fundamental characteristics, particle size, and the observed combustion profiles. Empirical expressions for the duration of each combustion stage have been derived. These have been validated with basic modelling including the predicted devolatilisation stage calculated by the FG-Biomass model (Chen et al.,1998).

1. Introduction

Use of biomass as a fuel for electricity generation has, up until recent years, been a rather marginal application and the preserve of small scale installations. With the pressures of EU requirements to reduce nitrogen oxide pollution [4] and increasing political weight behind greenhouse gas emission controls, biomass has become a fuel choice for some of the largest power generation plant in Europe. It is likely that more conversions and perhaps new dedicated "flexi-fuel" conventional thermal power stations will feature in many European states' energy policies. Indeed, the UK government 2012 bioenergy strategy recognises large scale power generation from biomass as being a key technology for the transition to a decarbonised electricity sector by 2050 [1]. By 2020, it is projected that the UK will have over 30 TW h of electricity

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generation derived from combustion of up to 16 million dry tonnes of biomass [5].

For over a decade, most biomass in large scale operations has been crudely inserted into the existing fuel handling stream of conventional coal-fired stations. This co-firing, at levels of 10% (by mass) or so has been a relatively simple means of displacing some of the coal and associated pollutants without significant alteration to the mills or burners. However, 2013 saw the first 100% biomass-fired 645 MWe unit at Drax coming on-line - an unprecedented scale for electrical power generation in the UK.

Plant of such scale (>0.4 GWe) requires more than 1 GW of thermal input. Furnaces in conventional coal power stations of this size favour the use of pulverized fuel burners, coal having a tendency to pulverize consistently and reliably. Biomass, on the other hand, is less disposed to fracture uniformly especially transverse to the fibre alignment of anisotropic cellulosic materials. Whereas coal can be broken-down to <100 μm particle sizes without excessive effort, similar milling effort on woody biomass can result in a spread of particle sizes and shapes ranging up to 3 mm or so [2]. Since most solid biomass fuels have around 80% volatile content and generally less than 20% "fixed carbon", the burning profile differs somewhat from that of coal. Biomass combustion in furnaces designed for pulverized coal therefore needs careful consideration to ensure effective operation. The volatile combustion stage will tend to produce more rapid release of fuel energy in the early part of the furnace [6]. Larger particles can extend the period of heat release in this stage but the remaining char will also have an extended burn-out time, this can be at the expense of a high proportion of un-burned char passing through to the ash [7] or particles dropping out of suspension unburned in the furnace. Achieving a good balance between milling effort, heat release profile and char burn-out is therefore one of the main challenges for efficient use of biomass in conventional plant. Particle size and shape is therefore a key variable to be controlled so understanding the effects of particle size for various biomass is important.

In order to model and predict the combustion behaviour of pulverized biomass in large scale furnaces, some have taken a fundamental approach whereby the combustion of a single particle is used as a sub-model (e.g. [8]). This approach requires the model of the single particle combustion to be refined before meaningful larger scale combustion can be extrapolated. The fundamental approach also requires good knowledge of the physical and chemical characteristics of the material such as thermal conductivity, heat capacity, porosity and kinetic parameters for pyrolysis and char combustion. Few, if any of these are known precisely for any given biomass fuel and there is a general paucity of experimental data to draw upon for refining and verifying such modelling.

Yang et al. [8] developed a computational model including heat transfer, mass transfer and chemical kinetics for cylindrical shaped particles in the range 0.5–20 mm. While this compared favourably to experimental data presented for a single particle burning in entrained gas flow, a more robust validation would require more extensive experimentally derived data to be produced, covering the range of particle sizes. Other useful single particle modelling approaches have been set out by Haseli et al. [9] and Saastamoinen et al. [10].

Experiments on single particles of biomass have practical limitations in replicating the conditions in a pulverized fuel (p.f.) furnace. However there have been a number of experimental methods documented which examine combustion behaviour of biomass particle dimensions in the order of 1 mm [11–15]. These have investigated the influence of variables including particle size and shape, gas temperature and oxygen concentration with the intention of informing and validating models.

Flower and Gibbins [11] developed apparatus in which single particles of biomass were suspended on a wire mesh and heated to 900 °C in less than 0.5 s using an electrical element radiant heater. Experimental data for the drying, devolatilisation and char burn-out was obtained for European Ash wood with differing moisture contents.

Lu et al. [12] suspended single particles in an enclosed chamber reactor with a pre-heated air/nitrogen feed and internal heating elements enabling gas temperatures up to 1037 °C. Using poplar wood and hardwood sawdust particles in the size range 0.3–9.5 mm, the experiment focussed on the effects of shape differences on devolatilisation times, demonstrating that shape and aspect ratio differences affect the heat transfer and thereby show measurable differences in pyrolysis rates. Lu and Baxter [13] proceeded to directly measure the internal thermal gradients produced in these conditions using thermocouples in the centre and surface of 11 mm diameter particles. The data from this was used for validation of CFD modelling by Gubba et al. [14].

Momeni et al. [15,16] developed experimental apparatus using a gas burner and mass flow controllers to control the temperature and oxygen concentration in a vertical tube reactor in which single particles were placed for observing the combustion behaviour. The experiment examined ignition, devolatilisation and char burn-out for cylindrical particles with similar mass (12.5 mg) with aspect ratios ranging from 1 to 6 and for gas temperatures ranging from 1200 °C to 1600 °C (with oxygen concentrations ranging from 5 to 20% for the burn-out tests). Similar experiments performed by Riaza et al. [17] using a drop tube furnace and high speed camera on moving particles milled to < 150 μm, report burnout times for various biomass and oxygen concentrations.

While it is recognised that "biomass" fuel covers large variations, previous experiments have tended to examine only one or two materials with a relatively small number of data points. The time-consuming and laborious nature of preparing and burning individual particles places a limit on the volume of data that can be easily extracted.

In this investigation, we present an experiment examining the correlations between particle mass and the combustion behaviour; in particular, the conversion times for each stage of combustion, namely: ignition delay; volatile flame duration and char burn duration. In order to identify correlations amidst the variability and measurement noise, a large sample set (>100) has been used for each material.

2. Method

2.1. Preparation of samples

Three different biomass materials were selected for comparison: Pine, Eucalyptus and Willow. For consistency, the particles selected from the woody materials were selected without bark or obvious knotty structure (i.e. apparent as clean white wood).

Each particle was trimmed to a roughly cuboid/cylindrical shape using a razor to dimensions in the range 0.5 mm to 4 mm. The dimensions in the 3 principal axes were measured using a handheld micrometer (+/- 0.01 mm). Each particle was weighed on a microbalance (+/- 0.01 mg). Although the particle shapes were not precisely regular, a good estimate of the volume and surface area was obtained using the mean values calculated for a cuboid and cylinder with the same principal dimensions. The mean particle density for each material, as presented in Table 1, was derived from these measurements. These mean values were used subsequently to derive from the particle mass, an equivalent spherical particle size in heat transfer calculations.

Small batches of particle samples were wetted by adding small amounts of deionised water and storing in a sealed container