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## Research paper

# The combustion characteristics of high-heating-rate chars from untreated and torrefied biomass fuels

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## ABSTRACT

Torrefaction of biomass is of great interest at the present time, because of its potential to upgrade biomass into a fuel with improved properties. This study considers the fundamentals of combustion of two biomass woods: short rotation willow coppice and eucalyptus and their torrefied counterparts. Chars were prepared from the untreated and torrefied woods in a drop tube furnace at 1100 °C. Fuels and chars were characterised for proximate, ultimate and surface areas. Thermogravimetric analysis was used to derive pyrolysis and char combustion kinetics for the untreated and treated fuels and their chars. It was found that the untreated fuels devolatilise faster than their torrefied counterparts. Similarly, the chars from the untreated biomass were also found to be more reactive than chars from torrefied fuels, when comparing reaction rates. However, the activation energy value ( $E_a$ ) for combustion of the untreated eucalyptus char was higher than that for the torrefied eucalyptus chars. Moreover, the eucalyptus chars were more reactive than the willow char analogues, although they had seen a lower extent of burn off, which is also a parameter indicative of reactivity. Similar trends in were also observed from their intrinsic reactivities; i.e. chars from the untreated fuel were more reactive than chars from the torrefied fuel and eucalyptus chars were more reactive than willow chars. Chars were also studied using scanning electron microscopy with energy-dispersive X-ray analysis. This latter method enabled a semi-quantitative analysis of char potassium contents, which led to an estimation of potassium partitioning during char formation and burnout. Results show a good correlation between potassium release and percent burnout. With respect to the effect of torrefaction on fuel-N, findings suggest that torrefaction would be beneficial for pf combustion in terms of nitrogen emissions, as it resulted in lower fuel-N contents and ~72–92% of the fuel-nitrogen was released with the volatile fraction upon devolatilisation at 1100 °C.

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## 1. Introduction

The use of biomass in UK power stations has increased considerably in recent years, either for co-firing with coal or for dedicated biomass burners. It has been estimated that approximately 2.9 million oven dry tonnes of solid biomass was used for electricity generation in the UK in 2011; with predictions that this usage will increase by 3–5.5 times the stated amount by 2020 [1]. Co-firing is also a popular technology for the reduction of carbon emissions in other European countries and North America. While biomass combustion has some similarities to coal combustion, there are significant differences in some aspects, e.g. the kinetics of devolatilisation and char burnout.

Torrefaction is a promising technology, as it has been shown to improve biomass properties and therefore has the potential to increase the usage of biomass in pulverised fuel (pf) combustion. During torrefaction the appearance and handling properties of the untreated wood are changed, and the resultant darker fuel has higher energy density, and improved hydrophobicity and grindability (e.g. Refs. [2–8]). Moreover, the chemical composition of the fuel is modified, resulting in differences in C, H and O contents, as well as a decrease in volatile matter due to partial or complete degradation of hemicellulose, and partial decomposition of lignin – and possibly even cellulose fractions – depending on the degree of processing [8–11]. These changes are expected to impact on the combustion behaviour of the pre-treated fuels, such as devolatilisation and char burnout reaction kinetics. Char burnout kinetic data of untreated biomass and torrefied biomass in relation to applications in power stations and in CFD modelling are scarce [12]. Previous studies on kinetics of biomass char burnout have

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mostly focused on the study of slow-heating rate chars, e.g. Refs. [13,14]. There have also been studies on the combustion and char burnout of torrefied biomass at high heating rates, such as those encountered in a drop tube furnace [12,15,16] and more recently, studies specifically on torrefied biomass high heating rate chars [17,18]. Nevertheless, still little is known about detailed surface areas of the resultant chars to enable intrinsic reaction rates to be determined.

Another unknown is the partitioning of potassium and nitrogen during high heating rate devolatilisation. Potassium is an important catalytic metal for both the pyrolysis stage and the char combustion stage [19–21], therefore its fate upon torrefaction and fast pyrolysis would also impact on the reactivity of the resultant char. Another critical impact of potassium is the deposition of its salts in boilers and furnaces, and so knowledge of potassium partitioning during combustion is extremely valuable. With respect to nitrogen oxides (NO<sub>x</sub>), it is expected that the displacement of coal by biomass would result in a decrease in these emissions, since most biomass fuels have lower nitrogen concentrations than coals (usually <1%) [22]. In practice, findings are mixed since there are other factors that influence the formation of NO<sub>x</sub>, such as burner configuration, flame temperature, char burnout and other process conditions. Hence, data on partitioning of fuel nitrogen between volatiles and char is needed for the development of a firing strategy that would assist in achieving low NO<sub>x</sub> emissions. In such a scenario, it is necessary to understand the role of torrefaction and its effect on nitrogen behaviour upon devolatilisation and char formation.

The methodology used in this study was to prepare chars from short rotation willow coppice and eucalyptus, as well as from their torrefied counterparts at high heating rates and high temperature in a drop tube furnace, therefore comparable to those conditions encountered in industrial boilers. Chars were collected for examination and their reactivities were determined by means of thermogravimetric analysis (TGA). Kinetic parameters were also derived for the decomposition of the untreated and treated fuels from TGA data. Furthermore, the evolution of potassium and nitrogen during both torrefaction and char formation were also examined. The data obtained was then used to provide information on the behaviour of the fuels in high temperature combustion in pf flames.

## 2. Experimental

### 2.1. Samples

For this study two fuels sourced from local farms in Yorkshire, short rotation coppice willow (*Salix* spp.) and eucalyptus (*Eucalyptus gunnii*) and their torrefied counterparts, obtained from a previous study [10] were milled using a Retsch PM 100 ball mill at 250 rpm for 4 min and sieved to obtain a size fraction of 212–355 μm. The samples were then oven-dried at 80 °C for 24 h prior to the char preparation step. The torrefied samples were prepared under a nitrogen flow of 1.2 L min<sup>-1</sup> at a heating rate of 10 °C min<sup>-1</sup>, with a drying step at 150 °C for 60 min. This was followed by programmed heating at a rate of 10 °C min<sup>-1</sup> to a final temperature of either 270 or 290 °C for either 30 or 60 min residence time, as follows: 270 °C for 30 min (Willow 270/30, Eucalyptus 270/30), 270 °C for 60 min (Willow 270/60) and 290 °C for 30 min (Willow 290/30, Eucalyptus 290/30). In this instance, the residence time is defined as the dwell at the final temperature. Detailed information about the torrefaction process and full characterisation of the untreated and treated samples can be found in Ibrahim et al. [10].

### 2.2. Drop tube furnace char preparation

High heating rate chars were prepared from each untreated and torrefied fuel in a drop tube furnace (DTF), for which a schematic is shown in Fig. 1. The DTF consists of an alumina tube of 1400 mm L × 65 mm i.d. inserted in an electrically heated vertical furnace (Elite Thermal Systems), with three independently heated zones and an isothermal reaction zone of 455 mm. The reaction gases consisted of pure nitrogen at a flowrate of 16 L min<sup>-1</sup> and entrained air in order to ensure an oxygen concentration of 1.0 ± 0.2%, which was continuously monitored using a Mitchell Instrument XTP601 paramagnetic analyser. The 1% oxygen was implemented to prevent the biomass chars sticking to the inside walls of the reactor. The gas flow rates used were found to result in Reynolds numbers that fell well within the laminar zone for the process temperature used. Furthermore, a vacuum pump ensured the gases flowed isokinetically through the reactor. All chars were prepared at a DTF temperature set at 1100 °C, with a residence time of ~0.5 s in the reaction zone—assuming the particles travel along the reactor centreline. The temperature profile measurements of the reaction zone, measured at seven points alongside the centreline of the reactor using a K-type thermocouple resulted in an average temperature of 1062 ± 33 °C. The inlet of the reactor consists of a water-cooled feeding tube to prevent the reaction of particles before the isothermal heating zone is reached. The chars

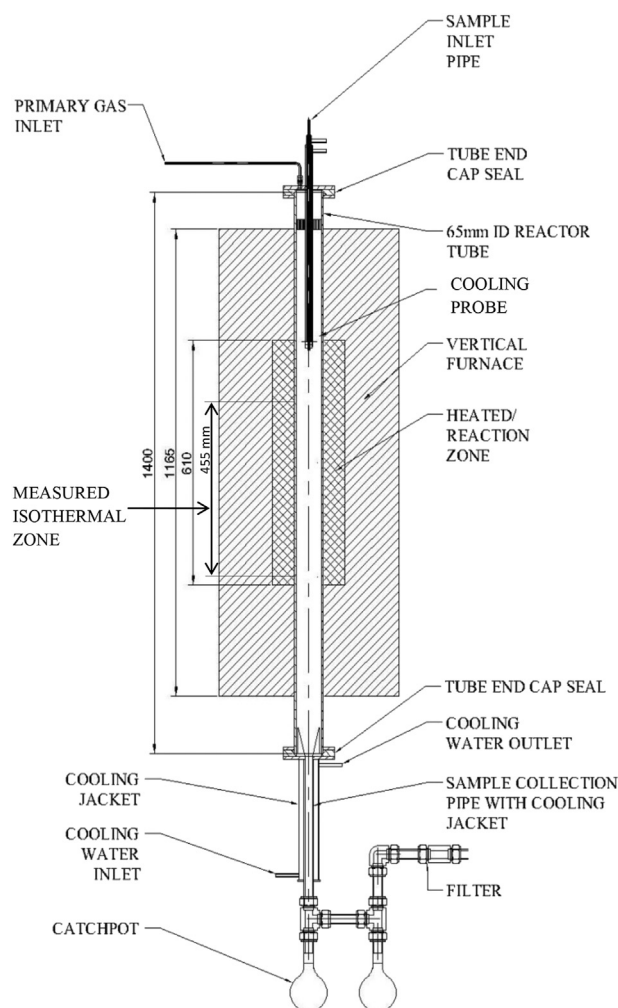


Fig. 1. Schematic of the drop tube furnace.

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