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# Steam gasification of rapeseed, wood, sewage sludge and miscanthus biochars for the production of a hydrogen-rich syngas

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ABSTRACT

Steam gasification of biochars has emerged as a promising method for generating syngas that is rich in hydrogen. In this study four biochars formed via intermediate pyrolysis (wood pellet, sewage sludge, rapeseed and miscanthus) were gasified in a quartz tubular reactor using steam. The dynamic behaviour of the process and effects of temperature, steam flow and particle size were studied. The results show that increases in both steam flow and temperature significantly increase the dry gas yield and carbon conversion, but hydrogen volume fraction decreases at higher temperatures whilst particle size has little effect on gaseous composition. The highest volume fraction of hydrogen, 58.7%, was obtained at 750 °C from the rapeseed biochar.



## 1. Introduction

As the move towards sustainable energy generation gathers pace, renewable technologies are being implemented all over the world and the UK is no exception. According to the Department of Energy and Climate Change (DECC), renewable electricity accounted for 9.4% of the total electricity generated during 2011 and renewable energy as a whole accounted for 3.8% of the UK's total energy supply; an increase from 3.2% in 2010 [1]. Biomass use in particular is increasing rapidly as a result of its versatility in feedstock and applications, which covers a wide range from direct combustion for heat and power, biofuel synthesis to value added chemicals. In 2010, bioenergy accounted for 38% of the total renewable energy generated in the UK. This share is set to increase as coal power stations such as Tilbury B are converted from coal to dedicated biomass burners [1]. In order to maximise the use of available feedstock, advanced thermochemical technologies such as pyrolysis and gasification must be utilised, since these technologies enable low quality biomass fuels and residues to be upgraded into more valuable forms [2].

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Pyrolysis is described as the thermal decomposition of carbonaceous matter into a range of useful products, in the absence of an oxidising agent. It is carried out at medium to high temperatures (350–650 °C) and gives three products; liquids (bio-oil), gases (CO, $CO_2$, $H_2$, $CH_4$ up to $C_6H_6$) and char (biochar if biomass is the starting material) [3]. Three modes of pyrolysis have been developed – slow, fast and a new type, intermediate pyrolysis. Heating rates used in the process define the mode of pyrolysis. Table 1 compares the three modes [2] [4].

Slow pyrolysis or carbonisation is used to produce biochar whilst fast pyrolysis is optimised to produce bio-oil. These processes are commercially important as the products can be used in a variety of processes such as combined heat and power (CHP) generation, biofuels and chemicals [2]. Although successful applications have been developed with woody biomass, non-woody biomass can lead to bituminous products which solidify at room temperature [5]. Intermediate pyrolysis enables a diverse range of products such as waste wood, food waste, grass and algae to be utilised [5]. One type of intermediate pyrolysis utilises the pyroformer reactor. It comprises counter rotating coaxial screws to move the feed along the reactor and allows for easy control of solid residence time. Heat transfer is aided by the use of metal spheres, negating the need for costly feed preparation associated with fast pyrolysis [6].

The biochars produced from intermediate pyrolysis have a high carbon content, low volatile content and are reactive enough to be gasified by either steam or $CO_2$ [7]. Many reactions occur during the steam gasification process. The main ones are shown in Table 2 below.

Interest in the area of steam gasification of biochars has grown considerably. Yan et al. [9] carried out steam gasification experiments of pine sawdust biochar in a fixed bed reactor. They reported an increase in hydrogen volume fraction with increasing temperature as a result of further cracking, and at 850 °C, 52.4% hydrogen (on a dry basis) was obtained, with a steam flow of 165 g $min^{-1}$ $kg^{-1}$ biochar. In another study [10], the same authors investigated the effects of particle size and temperature on biochar derived from the fast pyrolysis of cyanobacterial blooms. They reported that varying the particle size had little effect on the gaseous composition or the yield of gas produced. Chaudhari et al. [7] gasified bagasse biochar using steam and reported a maximum hydrogen volume fraction of 51.2%. In another study [11], the same authors gasified bagasse and commercial biochars in a fixed bed microreactor. They reported a very high hydrogen volume fraction (76.2%) at 700 °C and low steam flow rates (20.8 g $min^{-1}$ $kg^{-1}$ char), which decreased to 70% at 800 °C at the same steam flow rate. At higher steam flow rates (167 g $min^{-1}$ $kg^{-1}$ char), no overall trend was reported in the hydrogen content as it behaved differently with respect to the chars tested. Zhang et al. [12] scaled up biochar gasification using a fluidised bed reactor and reported that although the volume fraction of hydrogen increases slightly with increasing temperature from 750 to 900 °C, no clear trend was reported.

The above investigations were all carried out using biochars from fast pyrolysis. Significant differences exist between pyrolysis modes and these differences have a major effect on the biochars produced. For example, Chen et al. [13] investigated the reactivity of biomass chars from rapid and slow pyrolysis using steam and $CO_2$. They reported that chars from rapid pyrolysis showed a reactivity that was three times higher than those formed by slow pyrolysis. Previous studies have also failed to provide a link between the physico–chemical properties of the biochars and their behaviours during the steam gasification process. The main aim of this study was to investigate whether four biochars; wood pellet biochar (WPB), rapeseed biochar (RSB), sewage sludge biochar (SSB) and miscanthus biochar (MCB), all formed via intermediate pyrolysis, can be used to produce a high quality syngas that is rich in hydrogen. Other aims include finding the optimum conditions to produce such a gas; determining which biochar is most suitable for hydrogen production and; to determine the physico-chemical effects of the biochar on the gasification process and to shed new light on the dynamic gasification behaviour.

## 2. Materials and methods

The biochars used in the study were produced in the Pyroformer at Aston University, using intermediate pyrolysis and the gasification studies were carried out at the University of Birmingham. The precursor biomass substrates were acquired

**Table 1 – Comparison of the three modes of pyrolysis [2,4].**

| Pyrolysis mode | Conditions | Product distribution (g $kg^{-1}$ initial dry feedstock) | | |
|---|---|---|---|---|
| | | Liquid | Char | Gas |
| Fast | Reactor temperature: ~500 °C<br>Heating Rates: >1000 °C $s^{-1}$<br>Hot vapour residence time: ~1 s<br>Solid residence time: ~1 s | 750 | 120 | 130 |
| Intermediate | Reactor temperature ~ 400–500 °C<br>Heating rate range: 1–1000 °C $s^{-1}$<br>Hot vapour residence time ~ 10–30 s<br>Solid residence time: 1–30 min | 500 | 250 | 250 |
| Slow | Reactor temperature ~ 300–500 °C<br>Heating rate: up to 1 °C $s^{-1}$<br>Solid residence times: ~ hours–days. | 300 | 350 | 350 |