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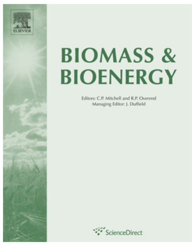

An investigation into the effect of fast heating on fluidity development and coke quality for blends of coal and biomass

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ABSTRACT

The addition of biomass to coking coals can reduce operational costs and carbon emissions but also reduces fluidity development. The use of heating rates up to 20 °C min^{-1} in the softening stage of coal has been investigated using high-temperature small-amplitude oscillatory-shear (SAOS) rheometry to improve the fluid characteristics of binary blends of two coking coals with Scots pine. The effects of biomass concentration and particle size, biomass torrefaction, pellet mass and thermal pre-treatment of the blend on fluidity development and semicoke strength have also been studied. Fluidity increased with an increase in heating rate and an increase in the final temperature for fast heating. Relationships were found between the minimum complex viscosity of the blend, the heating rate and the concentration of biomass, which have been used to propose an equation to calculate the heating rate necessary to achieve optimum fluidity for a particular blend with biomass. The fluid characteristics of the blend were not affected to a great extent by the particle sizes of the biomass studied (<500 μm and >500 μm) or the torrefaction of the biomass (250 °C for 1 h in N_2), were increased by an increase in pellet mass, and were destroyed by blend pre-heating. The semicoke strength of the blend with a mass fraction of 10% Scots pine and fast heating (10 °C min^{-1}) proved to be higher than that of the coal alone with slow heating (3 °C min^{-1}) and resulted in a 3% reduction in non-renewable carbon emissions.

1. Introduction

The use of biomass as additive in coking blends offers the advantages of reducing production costs by replacing expensive prime coking coals and also reducing non-renewable carbon emissions into the atmosphere as biomass is carbon neutral. This neutrality is based on the assumption that the carbon released by biomass is re-captured from the atmosphere during photosynthesis. Most of the research to date on blends of coal and biomass has focused on the characterization of the pyrolysis behaviour of coal and biomass blends through thermal gravimetric analysis to elucidate possible synergistic effects [1–4]. This research has found contradictory findings regarding the degree of interaction between the components, which have been attributed to differences in pyrolysis conditions (e.g. reaction system, sample

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mass, heating rate) or sample characteristics. However, there is little research related to the effects of biomass addition to coking blends in terms of fluidity development and coke strength during carbonization. Some studies have found that the fluidity of the coking blend [5,6] and the coke strength [7,8] are usually reduced by the addition of biomass. However, there are several factors that can be varied to improve fluidity development and coke strength. Some of these factors include the heating rate during carbonization and the particle size of the biomass.

It is well known that an increase in heating rate is accompanied by an increase in the amount of fluid material in coal whilst the plastic zone extends towards higher temperatures as indicated by Gieseler plastometry [9,10]. This has also been observed through high-temperature rheometry [11] by showing a decrease in the minimum complex viscosity (i.e. increase in fluidity) and a shift in the temperature of maximum fluidity to higher temperatures as the heating rate increases. Thus, fast heating rates could potentially be used in blends of coal with biomass to achieve similar fluid characteristics that the coal alone under typical heating conditions in coke ovens during carbonization (i.e. 3–5 °C min^{-1}). Indeed, blends with biomass have been proven to possess similar fluid characteristics that prime coking coals as long as the heating regime is increased significantly from 3 °C min^{-1} to 180 °C min^{-1} just before coal softening [6]. However, these fast heating rates are not feasible for commercial application and further investigation is required to ascertain whether lower, more realistic heating regimes can still improve the fluid characteristics of the blend.

On the other hand, the effect of biomass particle size on fluidity and coke strength has also been studied in woody biomass and charcoal. Lower particle sizes for charcoal have been reported to cause a higher reduction in fluidity [10,12]. MacPhee et al. [8] found a sharp drop in coke strength with charcoal additions of 2–10% to coal blends, but an increase in the particle size of charcoal had a dramatic improvement on the quality of the coke produced with 5–10% additions. Similarly, Ota et al. [13] found that the reduction in coke strength caused by a waste wood was inhibited by an increase in particle size. These findings might suggest that coke strength could be compromised by low cohesion between coal and biomass. In this manner, Matsumura et al. [7] proposed that it is necessary to decrease the contact area between woody biomasses and coke in order to increase the addition of biomass without lowering coke strength. These authors identified the low bulk density and collectability of the biomass as the main drawbacks in their use as additives in coking blends, and they proposed that compressive forming at 200 °C could effectively decrease the contact area by increasing both particle size and density.

There is another problem associated with biomass in coking blends, namely its high volatile matter content that will cause a reduction in coke yield. This drawback could be partially solved either by identifying biomass samples that produce high carbon yields during pyrolysis or by pre-treating the biomass sample. For instance, Diez et al. [5] studied *Eucalyptus* wood, its components xylan, cellulose and lignin, and the charcoal and tars obtained during carbonization, and found that charcoal and lignin possess the lowest conversion yield at the thermoplastic temperature range of coal (350–500 °C), and therefore, will produce the highest coke yield. Another way of reducing the conversion yield of the biomass and increasing its bulk density is by means of mild pyrolysis or torrefaction, which is a thermochemical process involving the slow heating of biomass to temperatures in the range 200–300 °C in the absence of oxygen [14]. The torrefied biomass is characterised by higher fixed carbon and atomic carbon, and the H/C and O/C atomic ratios resemble those of low rank coals [15,16]. Since the most reactive lignocellulosic component is hemicellulose, the composition of the biomass will have an effect on the amount of solid residue after torrefaction [15].

The present work expands on a previous study [6], which investigated the effect of different biomass on fluidity development in coking blends using high-temperature SAOS rheometry. The study found that up to 5% by weight of sugar beet can be added to coking coals without altering its viscoelastic properties, while the addition of pine wood or miscanthus had a negative effect on fluidity development which could be countered by fast heating to the softening temperature of the coal (i.e., 180 °C min^{-1} instead of 3 °C min^{-1}). The present work focuses on the determination of the optimum heating conditions in pellets of blends of coal with biomass in order to achieve optimum fluid characteristics without impairing semicoke strength. The effects of biomass particle size, biomass torrefaction, pellet mass and blend pre-heating on fluidity development have also been studied.

2. Materials and methods

2.1. Materials

This work was performed on two coals and wood substrates of unknown provenance, for which the chains of custody are not known. While the authors believe that this work exemplifies the difference between coals and the particle sizes of the biomass, there is a reasonable concern that there may be substrate factors that influence the general applicability of the results obtained. The characteristics of the coals used in this study, namely coals A and B, are presented in Table 1.

Scots pine (*Pinus sylvestris*) was supplied by BP and the proximate analysis is presented in Table 2.

Two particle size fractions of Scots pine were studied (<500 μm and >500 μm), and the biomass was also torrefied under nitrogen to increase its density and char yield. The <500 μm fraction was characterised by spherical particles whereas the >500 μm fraction was characterised by stick-like shapes of up to 0.5 mm in diameter and 3 mm in length. During torrefaction, the biomass was heated from 50 °C to 250 °C at 3 °C min^{-1} in nitrogen and thereafter the temperature was held at 250 °C for 1 h.

2.2. Methods

Small-amplitude oscillatory shear (SAOS) rheometry measurements were carried in a Rheometrics RDA-III high-torque controlled-strain rheometer. A detailed description of the analysis conditions can be found in the work carried out by