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Research article

Ignitability and combustibility of Yallourn pyrolysis char under simulated blast furnace conditions

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ABSTRACT

In this paper we have examined the potential of Yallourn brown coal char (collected from an industry-scale pyrolyser) to be used as a pulverized coal injection (PCI) fuel, its size-dependent properties, ignitability and combustibility under the simulated conditions of the blowpipe-tuyere section in a blast furnace. The combustion of individual sizes for Yallourn char was tested in a lab-scale drop-tube furnace (DTF) using pre-heated hot gas with a temperature up to 1000 °C, and a particle residence time as short as 0.6 s. Computational fluid dynamics (CFD) modelling was further conducted to optimize the char combustion conditions via sensitivity analysis. Irrespective of the pyrolysis condition, Yallourn char is superior over bituminous coal for being used as a top grade PCI fuel, due to its higher calorific value (7500–8110 kcal/kg), lower ash content (<10 wt%), high ash melting temperatures (>1550 °C), and abundance of iron (>40 wt% in ash). The performance of Yallourn char is also superior over bituminous coal under the simulated blast furnace conditions, for a rapid ignition and burnout even for a coarse char size of 300 μm under the stoichiometric O_2/C molar ratio and using low blast temperatures of 800–1000 °C. All these are beneficial for reducing the energy consumption related to particle pulverization and the amount of oxygen for the combustion. With regard to the Yallourn char ignition and combustion in the hot gas, a minimum 6 wt% volatile content is essential for a stable and rapid ignition of the volatiles at a gas temperature of 1000 °C or below, since homogeneous ignition is predominant at low temperatures. However, once the blast temperature rises to 1200 °C, the dependence on volatile content turns insignificant due to the dominance of the heterogeneous ignition, high C-O_2 reactivity for the solid char, as well as the minimized pore diffusion control due to the large porosity (52.0–63.1%) of the Yallourn char tested here.

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1. Introduction

With the depletion of the reserves for coking coal in the world, the demand for the use of PCI coal at a high coke replacement ratio is increasing stably in the international steelmaking industry [1]. PCI technology involves directly injecting coal into the blast furnace, increasing productivity, and replacing a part of coke that is used for the process of making iron [2]. The PCI coal has strict requirements in terms of ash composition and amount, volatile content, moisture content and grindability.

Volatiles present in a PCI coal have a double-edged role in blast furnace performance [3]. The injected coal has to devolatilize and combust at the correct location and time, for operational safety and optimal performance. Due to the very short residence times of coal particles in the raceway (15–20 ms), controlling combustion and ignition is critical to avoid incomplete burnout and excess unburnt char formation. While higher volatile content is correlated with higher char reactivity and hastened ignition [4], excessive amounts of volatiles may cause unstable combustion in the blowpipe and the degradation of coke [5]. Additionally, volatile content is inversely correlated with the calorific value of a coal. A low-volatile coal with a high calorific value will be able to replace a greater portion of the coke leading to additional cost savings with low volatile coals.

Reactivity of the PCI coal is another important factor in blast furnace performance [6]. In general, as PCI injection rate increases, unburnt char can increase the amount of fine coke particles in the raceway region, which in turn exerts detrimental effects on gas flow and permeability of the coke. However, a generalized conclusion regarding the impact of char reactivity on the performance of blast furnace has yet to be achieved. Phillip suggests that char reactivity may not be a significant factor in the raceway [7]. At the high temperatures in the raceway of up to 1500 °C, the char oxidation will be mainly diffusion controlled, and hence, its rate will be fast enough that any oxygen present at the particle surface will be consumed quickly [8]. On the other hand, Lu proposes that intrinsic char reactivity is a significant factor in burnout due to the highly turbulent regions in the flame and small particle sizes used in PCI combustion [9]. In addition to the char - O_2 reaction, the

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char - CO_2 gasification will occur beyond the raceway and this is likely to be intrinsically controlled due to the slower rate of reaction and lower temperatures in the furnace stack.

Low-rank brown coal has large reserves in both Australia and China, and also other parts of the world. However, due to its large moisture content, low-rank coal has been mainly used as the feedstock to supply local power plants which generally have a very low efficiency and a high carbon emission rate compared to black coal [10]. Little of low-rank coal is being used as a value-added product in the market for non-power applications including blast furnace use. Upon beneficiation such as mild pyrolysis, the low-rank coal is expected to be upgraded to a char with a higher calorific value that can be used in a variety of advanced applications including power generation, combustion in blast furnace, precursors for activated carbon, and reductants for the production of precious metals in the metallurgical industry. To date, the application of low-rank brown coal char as a PCI fuel for a blast furnace has yet to be tested. Instead, the use of woody charcoal as a PCI substitute fuel for CO_2 emission reduction has been examined [11]. Compared to woody charcoal, the low-rank coal char possesses distinct properties including different ash content and composition, as well as a different carbonaceous structure and reactivity.

This paper follows on from previous work on coal-char blends [12], and aims to validate the viability and benefit of fully replacing the commercial bituminous coal by brown coal char as the single PCI fuel in a blast furnace, rather than through blending them together. In particular, considering that volatile matter is one of the most critical factors for a single PCI fuel [3–5], the primary goal of this paper is to clarify the minimum volatile content in a lignite char that can ignite stably and rapidly while reaching its maximum possible calorific value (thus energy density). Such a goal is also significant for tailoring the parent coal pyrolysis conditions since the char is a prepared material, as well as establishing the bond between pyrolysis and the end-use of the pyrolysed char. To date, most of the studies on char properties and reactivity have failed to specify the end-use of the char, thereby providing little advice to both PCI application in the blast furnace, and to the optimisation of pyrolysis conditions to meet the needs required by the PCI application. Additional efforts were further made to reveal the maximum possible size for the lignite char that can burn efficiently, so as to reduce the energy consumption required for its milling prior to being injected into the blast furnace.

To achieve the afore-mentioned research objectives, two Yallourn char samples collected from a pilot-scale shaft furnace with a capacity of 200 kg/h have been characterized and tested in this study. Their size-dependent properties and intrinsic reactivity were firstly examined. Secondly, an experimental study of char particle ignition and burnout was conducted in a lab-scale thermogravimetric–differential thermal analyser (TG-DTA) and drop tube furnace (DTF) as a function of O_2/C molar ratio, furnace temperature and char size. The DTF used is unique, possessing the capability to provide a hot blast gas up to 1000 °C to mimic the industrial blast furnace. Finally, computational fluid dynamics (CFD) modelling was performed to interpret the DTF results and further explore the optimum properties for lignite char in terms of ignition and burnout under the simulated blast furnace conditions. The parent raw coal is sourced from the Latrobe Valley, Australia. As a reference, a bituminous coal currently used commercially as a PCI coal was analysed and compared.

2. Material and methods

2.1. Properties of Yallourn char products

Coal for the production of char is sourced from Yallourn in Victoria, Australia. Yallourn lignite has a very high moisture content (65.2% ar) but is low in ash (2.61% db) [13]. Two char samples were generated by pyrolysis of raw wet Yallourn lignite in a pilot-scale shaft furnace with a capacity of 200 kg/h at approximately 800 °C. These will be referred to as Yallourn char 1 (YC-1) and Yallourn char 2 (YC-2) and their approximate residence times are 5 and 10 h, respectively. A longer residence time is expected to generate a low-volatile char that thus has a higher energy density. Other products recovered from the pyrolysis included water, gas and coal tar.

Char particles were size segregated prior to analysis. The char produced ranged in diameter from less than 100 μm to over 8 mm. Interestingly, the sizes less than 1 mm in diameter are mostly present as powdery, darkish particles that are analogous to high-rank black coal, as evident in Fig. 1 which shows the size-dependent surface morphologies of YC-1. Instead, the chunk sizes larger than 1 mm are more like woody charcoal. This is because the woody fibres are abundant in the original lignite. Clearly, the lignite char studied here is intriguing, as its maceral composition is a combination of both black coal and woody biomass. Such a sample has yet to be probed.

To determine the crystal structure of char samples, X-ray diffraction (XRD) analysis was conducted in a Rigaku MiniFlex600 instrument. The char samples were demineralized with 1 M HCl washing for 3 h followed by rinsing with deionised water until the leachate turned neutral prior to the XRD analysis. A scanning speed of 0.1°/min was selected with a step size of 0.01° for a 2-theta angle from 10° to 70°. The maximum capable power of 600 W was used for the XRD characterisation. The samples were ground under the argon protection prior to the analysis.

2.2. Ignition temperature, volatile release and char-O_2 reactivity measurement in TG-DTA

Char ignition temperature was measured in TG-DTA (Shimadzu DTG-60H) and was defined as the temperature at the intersection of the tangent of the char mass at the initial point (horizontal line) and the tangent of the char mass curve at the peak of the DTA curve when the sample is heated at a rate of 10 °C/min. Samples were ground to a size of <106 μm to minimise the diffusion.

Intrinsic char-O_2 reactivity kinetic parameters were calculated using the direct Arrhenius plot method which is based on Eq. (1).

$$\ln\left[\frac{1}{(1-\alpha)}\cdot\frac{d\alpha}{dT}\right] = \ln\left(\frac{A}{\beta}\right) - \frac{Ea}{R}\cdot\frac{1}{T} \quad (1)$$

where β is the heating rate and α is the conversion. By plotting $\ln[\frac{1}{(1-\alpha)}$

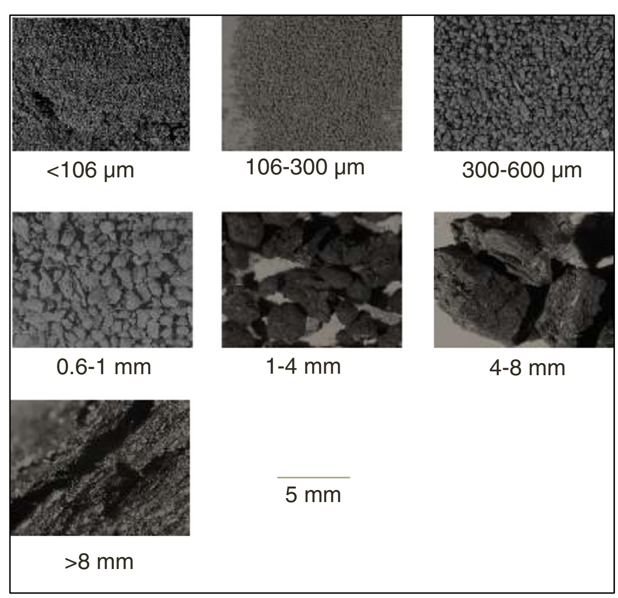

Fig. 1. Surface morphology of differently sized lignite char YC-1, observed by optical microscopy. Scale is relevant to all micrographs.

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