



# Opportunities to improve the utilisation of granulated coals for blast furnace injection



Julian M. Steer<sup>a,\*</sup>, Richard Marsh<sup>a</sup>, Mark Greenslade<sup>b</sup>, Andrew Robinson<sup>c</sup>

<sup>a</sup>Cardiff School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff CF24 3AA, United Kingdom

<sup>b</sup>Tata Steel UK, Port Talbot, United Kingdom

<sup>c</sup>Specific, Baglan Bay Innovation & Knowledge Centre, Central Avenue, Baglan, Port Talbot SA12 7AX, United Kingdom

## HIGHLIGHTS

- Blending coals improved the burnout of low volatile content semi anthracitic coals.
- Granulated samples showed a fragmentation effect in a drop tube furnace.
- Granulated particle fragmentation improved blend burnouts at lower residence time.
- Higher volatile content mass loss improved burnout at lower residence times.
- Included minerals with higher K/Al ratios gave non-additive burnout improvements.

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## ABSTRACT

Coal injection plays an important role to the economic success of ironmaking by substituting a portion of the coke input and improving the blast furnace productivity. Manufacturers are looking at opportunities to increase their coal selection options by using higher proportions of technically challenging lower volatile matter content coals; this paper investigates the kinetics, devolatilisation and burnout of these in granulated coal blends using thermogravimetric analysis (TGA) and a drop tube furnace (DTF).

The char residue from the semi-anthracitic low volatile coal selected for this blending investigation had a much reduced reactivity at higher conversions which affected the blends in different ways. Burnout of the blends with the low volatile bituminous coals was improved by fragmentation of the granulated particles, but at longer residence times the lower reactivity of the more structurally ordered carbon in the semi anthracitic coal dominated. In contrast, the higher volatile coals showed improvements at low residence times corresponding to rapid volatile loss, but also showed non-additive blend improvement at longer residence times which may be explained by the more obvious presence of included minerals and the higher K/Al ratios associated with illite mineral phases known to improve burnout.

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## 1. Introduction

Coal injection in the blast furnace is understood to reduce the consumption of expensive coking coals, increase productivity, increase flexibility in operation, improve the consistency of hot metal quality, and reduce the overall emissions from steel plants [1]. Typically, coal is injected into the blast line at temperatures around 1100 °C, and the particle residence time in the 'raceway' void formed by this hot blast is typically around 30–50 ms [2]; however, Guo et al. described work showing how raceway residence times could range from 25 to 1000 ms depending on the particle size due to turbulent conditions experienced in this region [3].

In most cases, coal is injected in a pulverised form where the particle size is typically below 75 µm; but this paper looks at granulated coal injection, which involves less energy to mill into specification, with a nominal sieve specification of 100% <1000 µm and 50% <250 µm [4,5]. However, the wider range and larger particle sizes are known to affect the devolatilisation and combustion of coals to a lesser or greater extent due to reasons such as heat transfer, mass diffusion, reactive surface area available, and maceral or mineral segregation affects [6–9].

Variability in coal properties can influence the quality of the hot metal, furnace stability, productivity and the off gas composition. Because of the short residence time in the raceway the devolatilisation and combustion of coal particles are vitally important, because unburnt particulates indicate un-utilised coal which increases the carbon input per tonne of hot metal and can interfere

\* Corresponding author. Tel.: +44 2920876765.

E-mail address: [SteerJ1@cardiff.ac.uk](mailto:SteerJ1@cardiff.ac.uk) (J.M. Steer).

with the permeability of the furnace [10–12]. For this reason the volatile content, or fuel ratio (fixed carbon/volatile matter), is often used by manufacturers as a measure of the suitability of a coal for injection and consists of combustible gases, incombustible gases, and condensable tars [13,14].

Higher volatiles generally have better combustion efficiency and produce more reactive chars and hence better burnout [15]. In comparison, low volatile coals with higher calorific values give better coke replacement ratios with less raceway cooling, but usually have lower combustion efficiency leading to unburnt chars [16,17]. However, higher volatile matter content coal can produce more soot which has lower reactivity than unburnt chars [18].

In order to utilise the optimum properties of both volatile scenarios, coals are often blended, but mixing has been found to alter the combustion properties depending on the coals chosen [16,19]. Kunitomo et al., found that high volatile matter coal formed a higher temperature combustion field that promoted the combustion of low volatile coals [20] whereas when Artos et al. blended high and low-rank coals they found it did not affect the combustion behaviour of the component coals when investigated in a thermogravimetric analyser or drop tube furnace [21]. However, there is also potential for individual coals to cause specific issues with grindability, combust at different rates and temperatures, and burnout at varying rates [18]. Recently Moon et al., showed non-additive behaviour between parent coals and their blends as the volatile matter content of the low rank coal (higher VM) influences the ignition temperature in the blend, whereas the char of the high rank coal (lower VM) in the blend influences the burnout temperature in the high temperature region [17].

Particularly important for the combustion of lower volatile content coals is the char reactivity and this has been studied in great depth [22–24]. The combustion of char is predominately controlled by chemical reactivity and pore diffusion of reactive and non-reactive gases in and out of the char [25–28]. The mineral content of coals, and the association of this in the coal, has also been shown to have an influencing effect on the devolatilisation and combustion giving effects that range from synergistic, catalytic or inhibitory depending on their levels and composition [29–34].

Although high volatile coals are often chosen for coal injection because of the concerns mentioned previously, more recently there has been a trend to utilise higher proportions of low volatile coals. However, increasing the proportion of these has the potential to reduce the furnace operation stability and increase top gas particulate emissions [1,18,35,36].

This paper measures the reactivity and burnout of coal blends with the more challenging high rank low volatile coals, aiming to establish the reasons how and why they affect the performance. In comparison to the state of the art, this work looks more closely at the use of granulated coals for blast furnace injection, instead of the pulverised coals more extensively covered by the literature for this application; it focuses on the novel way these coals and their blends fragment, swell and act synergistically on the burnout in a drop tube furnace.

## 2. Materials and methods

### 2.1. Materials

Five coals, ranging from the high rank semi-anthracitic LV1 to the lower rank high volatile bituminous HV, were chosen based on their variation in volatile matter shown in Table 1. The low volatile samples LV1, LV2 & LV3 ranged from 8.2% to 14.7% while the medium volatile MV was 24.6% and the high volatile HV up to 32.5%. For the investigation into coal blending, a 'reference' particle size specification was chosen, typical of a granulated coal specification for blast furnace injection, 100%  $\leq 1000 \mu\text{m}$  with 50%

$\leq 250 \mu\text{m}$ . The samples were milled to this specification using a TEMA™ disc mill and classified by dry sieving using the standard BS1016-109:1995. Because high rank semi-anthracitic coals can lead to unburnt particulates when injected into a blast furnace manufacturers are limited to how much they can incorporate, so for this research blends with 40 wt% LV1 were used.

The coal ash from each of the samples was analysed to identify the constituent elements and their variation, shown in Table 2, represented as the most stable oxide form.

### 2.2. Methods

#### 2.2.1. Proximate and petrographic analysis

The classified samples were dried at 105 °C using BS11722:2013 until a constant weight and the volatile matter content was measured using standard BS15148:2005. Ash contents were carried out using the standard method BS 1171:2010.

The petrographic maceral analysis was carried out in accordance with ISO7404 by preparing a polished particulate block and carrying out a point count under reflected light microscopy to identify the different macerals present.

A Perkin Elmer Optima 2100D inductively coupled plasma spectrophotometer (ICP-OES) was used to determine the analysis of metal in the coal ash. Samples were prepared for analysis by microwave digestion using aqua regia (1 part HNO<sub>3</sub>, 3 parts HCl), followed by hydrofluoric acid (HF, 48%) and boric acid (H<sub>3</sub>BO<sub>3</sub>).

TGA was carried out using a Perkin Elmer Pyris 1 TGA with an air flow rate of 30 mL/min at 4 different heating rates 5, 10, 15 & 20 °C/min. Kinetic analysis of the TGA mass loss and derivative data was used to determine the activation energy by standard BS ISO 11358-2:2005. Ozawa, and later, Flynn and Wall derived the relationship in Eq. (1), where  $E_a$  is the activation energy (kJ mol<sup>-1</sup>) and  $R$  is the gas constant which for the four different heating rates and temperatures becomes Eq. (2) for a given degree of conversion.

$$\log \beta + 0.4567(E_a/RT) = \text{constant} \quad (1)$$

$$\begin{aligned} \text{Eq. (1). Ozawa, Flynn and Wall model free kinetic relationship.} \\ \log \beta_1 + 0.4567(E_a/RT_1) &= \log \beta_2 + 0.4567(E_a/RT_2) \\ &= \log \beta_3 + 0.4567(E_a/RT_3) \\ &= \log \beta_4 + 0.4567(E_a/RT_4) \end{aligned} \quad (2)$$

Eq. (2). Ozawa, Flynn and Wall iso-conversional relationship.

By plotting the logarithm of the heating rate,  $\log \beta$ , against the reciprocal of the absolute temperature,  $T^{-1}$ , for each degree of conversion,  $\alpha$ , a series of straight lines were plotted from which the activation energy,  $E_a$ , was calculated from the slope ( $-0.4567E_a/R$ ) [37,38]. The measured activation energy quoted in Table 3 was obtained from the average activation energy for each degree of conversion plot.

Scanning electron microscope (SEM) images were obtained using a FEI SEM-EDX instrument XL30 ESEM FEG at 512 × 384 resolution in back scattered and secondary electron detection modes.

Particle size analysis work was carried out using a Malvern Mastersizer 3000 laser diffraction particle analyser using a wet cell accessory with obscuration levels between 4% and 8%.

#### 2.2.2. Devolatilisation and burnout testing using drop tube furnace

A drop tube furnace (DTF) was used to characterise the devolatilisation and burnout behaviour of the coal samples at 1100 °C in air for residence times between 35 ms and 700 ms. The high heating rate and short residence times in the DTF environment closely resemble those experienced when coal is injected into the blast air of the blast furnace raceway making this a particularly relevant technique [12,18,24,39]. Particles were fed into the top at feed

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