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Research article

Investigating char agglomeration in blast furnace coal injection

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ABSTRACT

Blast furnace iron manufacturers aim to reduce expensive coke usage through the injection of coal. This paper investigates contrasting agglomeration behaviour with a view towards optimising blast furnace operations and limiting furnace permeability issues.

A drop tube furnace (DTF) was used to investigate the performance of two coal particle size specifications that were representative of injection coal sizes: pulverised (100% < 300 μm, 50% < 75 μm), and granulated (100% < 1 mm, 50% < 250 μm). A range of coals was subjected to DTF testing with issues arising from the injection of caking coals. Results show these coals exhibit signs of agglomeration, a potentially problematic effect concerning blast furnace permeability. Considering gasification reactivity upon leaving the blast furnace raceway, it was found that the agglomerated coal chars do not suffer from poor reactivity and are more reactive than the non-agglomerated chars. Pre-treatment through oxidation was found to be an effective means of eliminating agglomeration in the DTF as a result of the reduction in caking properties.

1. Introduction

Coke is a crucial ingredient in blast furnace operation, used as a principal source of both fuel and reducing agent in smelting iron ore [1]. However, due to expensive coking costs it is now commonplace for alternative reductants, primarily coal, to be injected in order to limit coke requirements. Prior to injection, coal is ground to either pulverised or granulated specification. Pulverised coal is typically 60% < 75 μm, whilst granulated coal is coarser with top sizes of 1 to 2 mm [2]. Coal enters the blast furnace through injection lances within the tuyères causing the coal to be subjected to initial hot blast temperatures of around 1200 °C and heating rates of 10^4–10^6 °C/s [3–5].

Aside from cost savings by reducing coke demands, coal injection provides a range of processing, economic, and environmental benefits with improved furnace operability, higher productivity, and reduced plant emissions [6,7]. Coal injection has been known to generate various furnace challenges such as reduced flame temperatures and impacts on slagging, however, one of the most problematic issues and the primary concern for this work is furnace instability as a result of lowered permeability [8–10]. As the blast furnace is a counter-current reactor, both burden descent and efficient gas ascension are vital to stable operations meaning any reduction in permeability is an issue. Following injection into the furnace, coal char particles that remain unburned after leaving the raceway region are prone to accumulating, often causing blockages and thus lowering permeability [8,11–13]. Schott [14] explains that a key factor causing permeability issues is inefficient char gasification.

Under certain conditions, coal is prone to physical changes including swelling, fragmentation, and agglomeration [15–19] all of which will go on to impact particle reactivity. Upon the initial heating of a coal particle, caking coals are prone to developing plasticity, often occurring simultaneously with devolatilisation. With plasticity, the particle can become viscous and, as a result, there is the possibility of particles combining and resolidifying into larger particles called agglomerates [19]. Due to their now increased size, the particles have a smaller surface area available for reaction and thus are increasingly likely to leave the raceway region unreacted. Depending on the physical structure of the char leaving the raceway, an agglomerated char may be relatively unreactive, in turn increasing the likelihood of accumulation in the furnace – a factor in poor furnace permeability. Although Shampine et al. [20] determine that agglomeration has little effect on performance in typical combustors; no such conclusions have been drawn regarding effects in the blast furnace.

When studying char/agglomerate reactivity, it is important to consider the mechanisms that govern char reactions in the blast furnace. Under initial injection conditions in the raceway, coal oxidation rates are controlled by Regime III – the external diffusion of oxygen to the particle surface [21,22]. The high temperatures and relative abundance of oxygen available means that almost all oxygen transported to the surface of the particle is consumed [23]. As a result, surface area

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available for oxygen diffusion is the rate-limiting factor. Upon particles leaving the raceway and travelling into a limited oxygen/carbon-rich, lower temperature environment, the driving mechanism controlling char reactivity is Regime II – internal pore diffusion, with the physical structure of the char becoming the rate-limiting factor [21,22]. When discussing coal gasification in CO_2 Irfan et al. [24] state that the rate of gasification of a char particle in a high-carbon environment is governed by the accessibility of the reactant gas to the active sites located on the internal surface of the char. It is claimed that low reactivity will arise when a particle has a relative lack of large "feeder pores" thus resulting in gas diffusion in and out of the particle being driven through micropores as apposed to macro "feeder" pores. As a result of this, the physical structure of any char or agglomerate particle will impact reactivity in the blast furnace. Particles that react slowly will be susceptible to accumulating and impacting furnace stability [5].

This work aims to experimentally simulate coal injection and examine the possibility of agglomeration under blast furnace heating conditions by using a drop tube furnace (DTF). The experimental use of a DTF is common in investigating blast furnace coal injection [25–32] as a result of the high heating rates and low residence times provided that are akin to those in the blast furnace raceway region, whilst DTF temperatures of 1100 °C are suitable for replicating hot blast temperatures (900–1300 °C). Following DTF testing, the link between coal caking properties and agglomeration will be measured. Analysis of the physical structure of the agglomerated char and the gasification reactivity derived from this structure are assessed using scanning electron microscopy (SEM) and thermogravimetric analysis (TGA). In addition, heated pre-treatment is tested as a potential method of mitigating agglomeration. This study therefore extends our understanding of char agglomeration in blast furnace coal injection and the potential furnace impacts.

2. Material and methods

Four bituminous injection coals were chosen for analysis with the objective of including a range of volatile matter samples – one low volatile coal, two medium volatile, one high volatile. As both pulverised and granulated coal injection is common industrially, each coal sample was ground to both size specifications. A laboratory bowl mill was used to grind the raw coals prior to sieving (BS ISO 1953:2015) to the required size in accordance with industrial specifications. The specific sizes are detailed below:

Pulverised − 100% < 300 μm, 50% < 75 μm.

Granulated − 100% < 1 mm, 50% < 250 μm.

Following preparations for size, the samples were dried prior to proximate analysis (BS 17246:2010) and petrographic analysis (BS 7404-5:2009) with results shown in Table 1.

In order to simulate the injection of coal into the blast furnace, a drop tube furnace (detailed in [15,33] and shown in Fig. 1) was used. The drop tube furnace utilises high heating rates (10^4–10^5 °C/s) and short residence times (35 ms–700 ms) that can be adjusted to resemble the initial blast furnace hot blast and raceway environments. The initial heating of the injected coal particle is of particular importance to this work; therefore the aim was to provide a temperature similar to furnace hot blast conditions (typically 900–1300 °C [4]). As a result, an 1100 °C DTF operating temperature was selected with an air atmosphere. Coal samples were injected into the top of the 1100 °C furnace by means of a vibrating screw feeder at an addition rate of 30 g/h. The coal particles enter a nitrogen inlet gas before passing through the heated alumina work tube (1.36 m × 0.06 m) in an entrained laminar air flow (20 l/min). A particle residence time of 35 ms was selected by means of altering the length of a water-cooled collector probe to shorten the amount of time that the coal particles spend exposed to the heated furnace atmosphere. As the coal particles are entrained in the 20 l/min airflow, the distance required to set a specific residence time can be calculated via velocity of the gas flow and the desired residence time. The below equation was used where d = distance between injector probe and collector probe (cm), v = gas velocity (ms^{-1}), s = residence time (ms), whilst a correction factor of 5 cm is applied to allow for mixing of inlet gases.

$$d = 5 + (vs)$$

The cooled probe acts to quench the coal/char reaction, before leading to a cyclone trap whereupon the resultant char is collected prior to further analysis.

The extent to which the agglomeration effect found in the drop tube furnace will be observed in the blast furnace raceway is uncertain as the higher raceway temperatures may combust the coal to the extent that agglomeration is not present in particles exiting this region. However, it is well understood that the short residence times, varying raceway size, and competing raceway reactions could present conditions where coal is only partially consumed, allowing the potential for agglomeration in these partially burnt chars.

It is important to note that, as a result of the nature of agglomeration, there is potential for repeatability issues when creating chars/quantifying char agglomeration. All DTF runs and agglomerate quantifications were carried out a minimum of twice per sample with the averages shown.

Following char collection, back-scattered and secondary electron SEM images of the raw coal samples and the post DTF chars were attained using an FEI XL30 Environmental SEM with the aim of identifying smaller examples of particle agglomeration, in addition to linking the char reactivity with the char physical structure. In order to test char reactivity in a carbon-rich environment, a Mettler-Toledo TGA/DSC was used under a CO_2 flow rate of 100 ml/min. Prior to TGA analysis, char samples were devolatilised under nitrogen in order to remove the impact of volatiles and test the reactivity of the remaining carbon/mineral structure. Samples of 10 mg were held at 900 °C in CO_2 for 420 min whereupon mass loss was measured vs. time and used in order to calculate char conversion (x). The equation used to calculate conversion is shown below where m_0 = initial sample mass, m = instantaneous mass, and m_{ash} = mass of the char ash.

$$x = \frac{m_0 - m}{m_0 - m_{ash}}$$

A commonly used gasification figure was selected in order to indicate a char's reactivity; $t_{0.5}$ – the time in minutes taken for the chars to reach 50% conversion with a lower number signifying a more reactive char [34–36].

Specific surface area determinations were carried out using a Quantachrome Nova 2200e surface area and pore size analyser. 0.5 g of char sample was dried prior to vacuum degassing at 120 °C for 3 h. Following this the sample cells were analysed using BET theory with nitrogen used as the adsorbate gas. 5 specific surface area runs were collected for each sample and checked for consistency with the average used as the final specific surface area result, given in m^2/g.

In order to test the impact of coal pre-heating on agglomeration, the raw coal with the strongest agglomerating tendencies was selected for

Table 1
Proximate and petrographic analyses of dried coal samples.

Coal	Proximate analysis			Petrographic analysis		
	Volatile content (wt%)	Fixed carbon (wt%)	Ash content (wt%)	Vitrinite (vol%)	Liptinite (vol%)	Inertinite (vol%)
LV1	9.1	79.7	11.2	83	1	14
MV4	17.6	77.2	5.2	72	6	20
MV3	20.2	70.3	9.5	78	1	20
HV1	34.5	58.3	7.2	71	10	17