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Modelling the injection of upgraded brown coals in an ironmaking blast furnace

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ABSTRACT

Victorian brown coal is a low-cost and abundant resource, featuring in high moisture and low ash yield, and has a potential of replacing high grade metallurgical coals in pulverized coal injection (PCI) in ironmaking blast furnace (BF). In this paper, a three-dimensional mathematical model is used to simulate the flow and thermochemical behaviours related to the PCI operation of upgraded Victorian brown coals under full-scale BF conditions. The model geometry covers lance, blowpipe, tuyere, raceway and coke bed at the lower part of a BF. The typical phenomena of in-furnace aerodynamics and physicochemical behaviours relevant to the injection of Victorian brown coals are simulated, in terms of flow, temperature, gas composition and coal combustion characteristics. It is indicated that the model is able to predict the combustion phenomena of Victorian brown coals under BF conditions. The performance between one typical PCI coal and two upgraded brown coals by briquetting and pyrolysis, respectively, are compared. The results indicate the upgraded Victorian brown coal by pyrolysis under given conditions has demonstrated the similar combustion profile with the PCI coal, confirming the feasibility of replacing PCI coal with an upgraded brown coal. Compared with the other two coals, briquetted brown coal of relatively higher volatile matter (VM) led to the release of more fuel gas, thus consuming more oxygen and achieving higher temperature along the tuyere axial and along the raceway boundary. Faster combustion of briquetted brown coal also led to higher overall burnout around the raceway region. The model provides a cost-effective tool to optimize and control the injection of Victoria brown coals under industry-scale BF conditions.

1. Introduction

Victoria in Australia has one of the largest brown coal resources in the world, which is estimated to total 430 billion tonnes, and has been largely used for electricity generation in local power plants (http://earthresources.vic.gov.au). Compared with black coal, brown coal is relatively softer and younger, and has very high moisture content (~65 wt%) and much lower cost. Brown coal usually need to be upgraded or dried [1], to remove the massive moisture, before putting into use. Desirable characteristics, such as high reactivity, low sulphur, low ash content, cheap and abundant, make upgraded Victorian brown coal a promising solid fuel.

PCI is one of the most important improvements in ironmaking industry, it provides many benefits, such as reduce coke consumption, adjust furnace stability and cut CO_2 emission. Generally, pulverized coal particles are injected through an injection lance and carried by a stream of gas mixture introduced from blowpipe to form a high speed jet. Then coal combustion takes place in the raceway and the combustion of coke and coal generates massive heat in a short time [2,3]. The schematic of PCI technology and internal structure around raceway in a BF is illustrated in Fig. 1. Therefore, brown coal, as a lower cost fuel, has a potential of replacing conventional black PCI coal in BF operation if the brown coal products are able to demonstrate the similar combustion behaviour. But this technical feasibility has not been investigated in the past.

Previous research on combustion of Victorian brown coal is mainly on power plant [4–6], and has not been studied in ironmaking BF conditions yet. PCI is a very complex process. It is very difficult to get access into the lower part of BF due to its extreme working conditions. Lab experiment and plant test are expensive and labour-intensive. Modelling study provides a cost-effective method to study the comprehensive in-furnace phenomena, and has been studied from 1D e.g. [7], to 2D e.g. [8,9], where simulation conditions were simplified and some characteristics cannot be predicted. Only a few 3D modelling works can be found in the literature [10–12], for example, Nogami et al. proposed a 3D transient state model using CFD-DEM method, which is difficult to be applied to real blast furnaces as the number of coal particles is huge [10]. Du et al. reported a 3D PCI model covering blowpipe and

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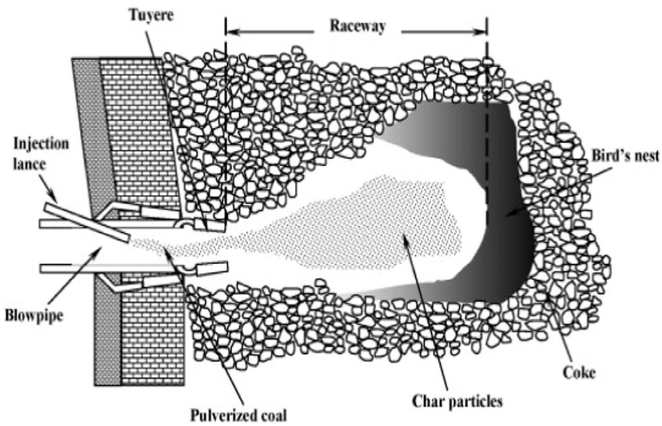

Fig. 1. Schematic of PCI technology and internal structure around raceway in a BF [4].

tuyere region and studied the impacts of tuyere design [11]. Guo et al. reported a 3D model to predict flow and combustion along tuyere centreline under pilot scale experiment conditions [12]. More details and more realistic conditions are desired. Shen et al. [13,14] developed a 3D PCI model to describe the complicated flow and combustion behaviours in the whole lower part of BF including raceway and coke bed for two fuels, i.e. coal and coke, and was used for investigating a range of operational parameters such as different types of black coals.

In this paper, Shen et al.'s model is applied to study the in-furnace phenomena of brown coals at the lower part of BF. Comparisons of the performance between one typical black coal and two upgraded brown coals are studied under BF conditions, in terms of flow, temperature, gas composition and coal burnout. Such comparison will help to investigate the technical feasibility of replacing metallurgical black coal with brown coals.

2. Model formulation

The model has been described in details in Refs. [13–15]. The model is outlined below for completeness. The model in this paper uses a single computational domain to cover the lower part of BF. Blowpipe-tuyere-raceway region is treated as a cavity, and coke bed is treated as porous medium. The following physicochemical processes are included in this model: (1) turbulent flow of gas-coal particle in the raceway and coke bed, (2) coal combustion process, including the devolatilization of coal, volatile matter combustion and char reactions, (3) gasification and combustion of coke, (4) heat transfer among gas-solid phase. The Computational Fluid Dynamics (CFD) model is developed on the platform of ANSYS-CFX 15.0.

2.1. Governing equations for gas-solid flow

A set of 3D, steady-state Reynolds averaged Navier-Stokes equations closed by the standard κ-ε turbulence model equations is used to describe the gas phase flow. The variables in the governing equations of gas phase are mass (m), particle number per unit volume (n_p), momentum (u, v, w), molecular diffusivity of species (Γ_i), drag force from particle (f_D), enthalpy (H), heat gain/loss by reaction (H_{reac}), and a number of species (Y_i), including O_2, CO_2, CO, H_2, H_2O and VM.

Lagrangian method is used to track coal particles along the discrete particle trajectories without considering interactions between coal particles. This is because, coal particle is treated as a dilute phase and the contact force between particles is not strong, considering raceway is a large cavity apace and it is of significant interest for PCI operation, compared to tuyere and blowpipe. Changes in particle movements are calculated by Newton's second law, where drag force and turbulent dispersion are considered. Three heat transfer modes are applied to the determination of temperature changes: convective heat transfer, latent heat transfer associated with mass transfer, and radiative heat transfer. They are outlined in Ref. [16]. The particle swelling due to the gas release during the devolatilization phase is considered in this model by assuming that the particle diameter changes is in proportion to the volatiles released [17].

$$m_p \frac{dU_p}{dt} = -f_D \tag{1}$$

$$-f_D = \frac{1}{8}\pi d_p^2 \rho C_D |U - U_P|(U - U_p) \tag{2}$$

$$C_D = \max\left(24\left(1 + 0.15\mathrm{Re}^{0.687}\right)/\mathrm{Re}, 0.44\right) \tag{3}$$

$$\text{where } Re_{fp} = \frac{\rho_f |U_p - U_f| d_p}{\mu_{f.}}$$

where m is mass, kg, U is mean velocity of gas, m/s, f_D is drag force from a particle, N, d is particle mean diameter, μm, ρ is density, kg m^{-3}, C_D is drag coefficient, Re is Reynolds number, and subscript f and p represents fluid and particle, respectively.

2.2. Chemical reactions and compositions

Combustion of pulverized coal is regarded as the following in sequence steps: preheating, volatile matter combustion, gaseous combustion and char oxidation. Coke is treated as pure carbon in this study, and coke consumption is refilled as a continuous phase in the modelling region. The gas compositions are obtained from the combustion of coal and coke in the domain, and composition of each gas is obtained by calculating the governing equations of each gas species i. More detail

Table 1
The proximate and ultimate analyses of black coal and brown coals.

Properties	Case 1 One black coal	Case 2 One upgraded brown coal by briquetting [25]	Case3 One semicoke (an upgraded brown coal by pyrolysis at 800 °C) [23,24]
Proximate analysis (ad)			
Moisture, %	3.2	9.3 (ar)	7.9 (ar)
Ash, %	9.8	8.9 (db)	3.1 (db)
Volatile matter, %	32.5	45.2 (db)	30.1 (db)
Fixed carbon, %	54.5	45.9 (db)	66.8 (db)
Ultimate analysis (daf.)			
Carbon, %	83.5	65.9	78.7
Hydrogen, %	5.3	4.4	2.7
Oxygen, %	8.6	22.31	14.49
Nitrogen, %	1.95	0.48	0.78
Sulphur, %	0.6	0.41	0.23

ad is air dried based, daf. is dried ash free based, ar is air-received, db is dried basis.

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