Minerals Engineering xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Modelling of injecting a ternary coal blend into a model ironmaking blast furnace

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ARTICLE INFO

Article history:
Received 16 August 2015
Revised 12 November 2015
Accepted 8 December 2015
Available online xxxx

Keywords:
Coal blend
CFD
Mathematical modelling
Blast furnace

ABSTRACT

The operation of ironmaking blast furnaces (BFs) involves several minerals such as iron ore, coals and flux. The practice of injecting a coal blend is widely employed in ironmaking BFs, typically binary blend or ternary blend. It is desirable to understand the overall performance of a coal blend and their individual behaviours of component coals. In this paper, a three-dimensional CFD model is described to simulate the flow and combustion of a ternary coal blend under simplified BF conditions. Three component coals in the ternary blend are tracked separately and undergo chemical reactions individually. The overall performance of ternary coal blend and individual behaviours of three component coals are analysed over the entire domain and quantified along the chamber axis, respectively, with special reference to flow, temperature, gas species and coal combustion efficiency. The simulation results show that generally, an inclined high-speed gas jet and coal plume are formed along the axis followed by an expansion and recirculation near the wall, resulting in the higher temperature and lower O_2 at the lower part of the chamber. Individually, the coal of higher VM content devolatilises faster, shows larger particle size downstream, and reaches a higher burnout and a slightly higher particle temperature in the end. The non-addition is observed in predicting the burnout of the ternary coal blend due to the interactions among three component coals. The model provides an effective tool for ternary blend's design and operation optimisation in ironmaking BFs.

1. Introduction

BF ironmaking is the dominant route to produce liquid iron from iron ore because of its high productivity and competitive cost compared to other ironmaking technologies (Ho et al., 2009; Ishii, 2000). In this process, several minerals are involved, such as iron ore, fuels e.g. coking coal and pulverized coal, and flux e.g. limestone (Shen et al., 2012). Reducing production cost is regarded as one of major task for BF operation (Hao et al., 2005; Shen et al., 2006). At present, pulverized coal injection (PCI) is considered as an effective technology to achieve this goal by partially replacing expensive metallurgical coke with low-cost pulverized coal. In practice, pulverized coal is injected with gas into the lower part of a BF via a lance through a nozzle (termed tuyere), and largely combusts in the raceway cavity (Fig. 1). As the rate of PCI increases, more unburnt chars are generated and accumulated at the lower part of BFs, leading to a reduced permeability and furnace stability. For this reason, it is expected to achieve a higher coal combustion efficiency (termed burnout) in the raceway of BFs.

Notably, as coke cost increases rapidly and PCI coal resources are depleting, most BF plants have to use various coal blends (mix of different coals) in PCI operation, rather than one single coal, to minimize the cost of PCI operation and to improve coal selection flexibility (Shen et al., 2008a). The flow and combustion of a coal blend is much more complex than a single coal, as the components may devolatilize and combust at different temperatures and at different times, and their burnout could therefore vary considerably. Therefore, it is important to understand the overall performance of a blend and the individual behaviours of components for designing coal blends and optimising PCI operation. On the other hand, other injectants such as plastic and biomass are attracting more attentions in PCI operation recently (Bürgler et al., 2007; Wang et al., 2014) and has a potential to be co-injected with coal into BFs.

In the past, binary coal blends (mix of two different coals) were studied experimentally (Assis et al., 2004; Du et al., 2010; Mathieson et al., 2005; Peralta et al., 2001) and computationally (Arenillas et al., 2002; Backreedy et al., 2005; Shen et al., 2009b; Sheng et al., 2004). For example, a pilot-scale PCI test rig was used to simulate the combustion of single and binary coal blends of coal plume under simplified BF conditions (Mathieson et al., 2005). It is regarded as one of the successful replications of PCI operation. On

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http://dx.doi.org/10.1016/j.mineng.2015.12.009

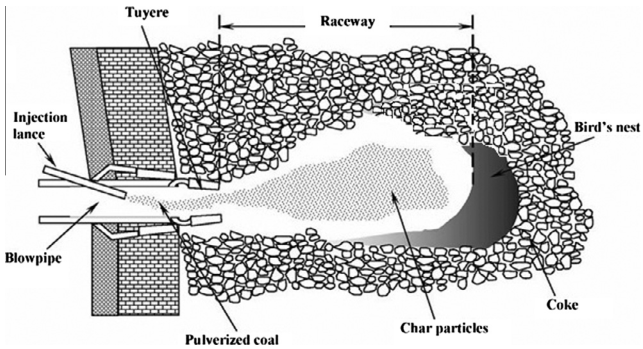

Fig. 1. Schematic of PCI operation in a BF.

the other hand, a CFD model was developed to simulate the flow and combustion of binary coal blends under the conditions of this test rig (Shen et al., 2009b). Nevertheless, this model was not able to simulate the combustion of coal blend for a wider range of coals due to model's limited applicability. Shen et al. (2011) reported an in-furnace model of PCI operation considering two fuels, both coal and coke for single coal combustion only. However, there is a lack of understanding of the flow and combustion of a ternary coal blend (mixing of three different coals) in BFs.

In this paper, a three-dimensional CFD model is extended to simulate the combustion of a ternary coal blend under simplified BF conditions. The devolatilization reaction model is improved for better applicability to a wider range of different coals. The model is validated against the experimental results from a pilot-scale combustion test rig. The overall performance of ternary coal blend and the individual behaviours of their component coals are analysed at two locations: over the entire domain and quantified along the axis, respectively, in aspects of flow, temperature, gas species and coal combustion. Then the burnout of ternary blend is compared with single coal combustion to investigate burnout enhancement.

2. Mathematical model

2.1. Model framework

The model was developed for binary coal blends under simplified BF conditions (Shen et al., 2009b). In this paper, this model is further improved in a few aspects such as including a more complex devolatilization model for better applicability to a wider range of coals, and thus able to simulate the flow and combustion of ternary coal blend. It is briefly described below for completeness. Gas phase flow is described by three-dimensional steady-state Reynolds averaged Navier–Stokes equations closed by the standard k–ε turbulence model. Equations solved for gas phase include mass, velocity, turbulence kinetic energy, turbulence dissipation rate, enthalpy and gas species mass fractions. Solid phase flow is treated as discrete phase and modelled using Lagrangian approach without considering physical interaction between coal particles, as it is a dilute phase. Three particle groups are employed to track the three component coals separately using over 500 representative particles for each component coal. Heat transfer between gas phase flow and particle phase flow is calculated including convective heat transfer, latent heat transfer, and radiative heat transfer. Full coupling of mass, momentum and energy are applied for gas–solid phases. The combustion of a ternary coal blend involves three chemically different coals, and each coal individually undergoes a series of chemical reactions: (1) preheating; (2) devolatilization of raw coal particles using two competing model (Ubhayakar et al., 1976); (3) gaseous combustion of volatiles using combined finite chemistry and eddy dissipation model (Magnussen and Hjertager, 1976); and (4) oxidation and gasification of residual char in the gas phase using Gibbs model (Gibb, 1985). The moisture content in the raw coals used in these simulations are very low and its impact is assumed negligible. Hence the moisture removal is not included in the model Detailed mathematical models for gas–solid flow, heat transfer and chemical reactions are described elsewhere (Shen et al., 2009c, 2009a).

2.2. Model modification

The model is modified by employing the so-called multiple fuel-gas treatment for VM considering its better applicability to a wider range of coals, covering from low volatile coals to high volatile coals (Maldonado et al., 2006), which may be the case for component coals in ternary coal blend. In the past, the so-called one fuel gas model was usually used for simplicity, where VM is assumed as C_xH_yO for both VM_1 and VM_2 in the two competing model, that is VM_1 and VM_2 are the same in composition. This treatment is applicable for both low and high volatile coals. The VM combustion is modelled as,

$$C_xH_yO + \left(x + \frac{y}{4} - \frac{1}{2}\right)O_2 \;\rightarrow\; xCO_2 + \frac{y}{2}H_2O$$

In this study, as the ternary coal blend may consist of different coals varying in a wider range of VM contents, VM is assumed to consist of a range of gases, as a result VM_1 and VM_2 may differ in composition:

$$C_xH_yO \;\rightarrow\; C_{x-1}H_{y-2z} + zH_2 + CO + H_2O$$

For simplicity, hydrocarbon was fixed to be methane CH_4, CO, CO_2 and H_2O. The reaction rate is computed to be the minimum of the finite chemistry rate and the eddy dissipation rate. The reaction kinetics of these gaseous combustion reactions are listed in Table 1. The model can be applicable to coal blends consisting of a wider range of coals, from low, mid and high volatile coals (Maldonado et al., 2006).

3. Simulation conditions

3.1. Coal property

Three different pulverized coals, denoted as Coal A, Coal B and Coal C, are blended and used as the ternary coal blend in this study. The proximate and ultimate analysis shown in Table 2, based on three Australian coals (Maldonado et al., 2006). Note that the same particle size distribution, $d_p = 50\ \mu m$ and $r = 1$ in Rosin Rammler distribution, are assumed in this study to exclude the effect of particle size on combustion.

3.2. Geometry and boundary conditions

The model is applied to a pilot-scale PCI test rig (Mathieson et al., 2005). Fig. 2 shows the geometry of main chamber and lance tip. In order to simulate the coal combustion in PCI operation, key features such as geometry setting of tuyere and lance, operational conditions and boundary conditions are reproduced in this model. In particular, the lance is introduced into the duct upstream of tuyere at an inclination angle of 6 degree to the duct axis with its tip on the axis. Three gas streams (conveying gas, cooling gas and hot blast) are introduced into the system. This geometry provides a realistic reproduction of the flow and thermo-chemical phenomena associated with the pulverized coal plume along the tuyere-raceway axis of a BF. Other operating conditions include (a), blast gas: 300 Nm^3/h, 1473 K, 20.9% O_2; (b), cooling gas: 3.2 Nm^3/h, 600 K, 20.9% O_2; (c), conveying gas: 2.0 Nm^3/h, 323 K. 100% N_2; and (d), the blend: 38 kg/h, 320 K.

Please cite this article in press as: Shen, Y.S., Yu, A.B. Modelling of injecting a ternary coal blend into a model ironmaking blast furnace. Miner. Eng. (2015), http://dx.doi.org/10.1016/j.mineng.2015.12.009