Model Study of the Effects of Coal Properties and Blast Conditions on Pulverized Coal Combustion

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High coal burnout within the raceway is important for the operation of a blast furnace. It is usually achieved by adjusting some operational parameters in practice. In this work, a three-dimensional model we developed recently is used to investigate the effects of some key operational parameters on coal burnout. The results confirm that notable improvements in final burnout can be achieved for coals with more fine particles and high volatile matter, and by higher oxygen enrichment. The use of high blast temperature can increase coal burnout, but the further increase in blast temperature over 1 200°C has little effect on final burnout. The effects of these parameters on other combustion characteristics are also analysed, in terms of volatile content, temperature field and gas species distribution, aiming to understand the underlying mechanisms behind these improvements. It is demonstrated that local oxygen supply is very important for high burnout in addition to coal properties. In addition, it is necessary to consider the raceway region when investigating the effects of these variables on coal burnout. This study helps identify appropriate and cheaper coals and optimise operating conditions to maximize the benefits of pulverized coal injection.

KEY WORDS: mathematical model; coal combustion; parametric study; blast furnace.

1. Introduction

Pulverized coal injection (PCI) into an ironmaking blast furnace is a significant technology for economic, operational and environmental reasons, including lowering the consumption rate of expensive coking coals and the subsequent extension of coke oven life, and increasing the productivity. 1,2) In a modern blast furnace with PCI operation, over 200 kg of coal per tonne of hot metal (kg/t-HM) can be injected; and over 300 kg/t-HM may be possible. 3) Nevertheless, as PCI rate increases, poor coal combustion within the tuyere and raceway could result in operational problems, including reduced permeability from unburnt char, and undesirable gas and temperature distributions (Fig. 1). Therefore, high coal combustion efficiency (also termed burnout) is desirable for high PCI operation as it affects the amount of coal that can be injected. Moreover, it is necessary to understand the coal combustion behaviour throughout the raceway and subsequent distributions of temperature and gas species in both tuyere and raceway. In practice, various operational parameters can be adjusted to improve the coal burnout, such as: coal properties (particle size distribution, coal type, coal preheating, 4) and coal blend, 5) operating conditions (blast temperature, oxygen enrichment, coal rate, additives, 6) tuyere diameter 7) and BiPCI 8,9), and tuyere/lance geometry design. 9-11) The coal properties and blast conditions are clearly important parameters. It is significant to carry out a systematic parametric investigation into the effects of these parameters on coal combustion behaviour in both tuyere and raceway, so as to provide not only know-how information but also know-why understanding for blast furnace practice.

Physically, coal combustion within the tuyere and raceway is a very complex process, involving turbulent multiphase flow, coupled with momentum/heat/mass transfer and various homogenous and heterogeneous chemical reactions. It is extremely difficult to carry out a comprehensive parametric study in full-scale blast furnaces due to hazardous conditions such as high temperature and high pressure environment and the requirement for stable operation. In this regard, laboratory experiments are widely used for such investigations, 3,12) but their operating costs are high and significant time is required. Moreover, these tests cannot always provide satisfactory insight information behind these improvements. Mathematical approach, especially computational fluid dynamics (CFD), provides a cost-effective
tool for understanding the effects of these operational parameters on coal combustion. Some CFD models were developed for PCI operation, as summarized elsewhere. In particular a few CFD studies on the effects of blast conditions and coal properties on coal combustion were reported in the past. Takeda and Lockwood reported a study using a two-dimensional model, demonstrating that notable improvements of burnout can be obtained with oxygen enrichment. Three-dimensional models are necessary for practical problems. Du et al. reported a three-dimensional numerical study of blowpipe and tuyere region in a blast furnace. Since the raceway was not considered, however, their conclusions could be misleading. For example, their results showed that coal burnout was hardly affected by oxygen enrichment, which is inconsistent with practice. In addition, some significant lance arrangements were not taken into account in the aforementioned two studies.

To overcome the problems identified above, in this paper, a three-dimensional model we recently developed is used to examine the effects of coal properties and blast conditions on coal burnout in a pilot-scale test rig relevant to blast furnace operation, where the raceway region and the lance details, although simplified, are included. In addition, the effects of these parameters on other combustion characteristics are analysed, such as temperature field and gas species distributions, so that underlying mechanisms of these improvements can be obtained. In particular, the insights of some experimental observations with little explanations, such as blast temperature, are explored. The findings are useful to the control and optimization of PCI operation.

2. Model Formulation

The present work is to numerically study the effects of coal properties and blast conditions on coal combustion in the tuyere and raceway cavity. It is based on the mathematical model we recently developed. As such, for brevity the model is only briefly described below.

In the model, the gas-solid flow is assumed to be steady state and three-dimensional. The gas phase is treated with an Eulerian frame of reference. The particle phase is modelled in a Lagrangian frame of reference with particle drag and turbulence dispersion included. The \( k-e \) model is used for gas turbulence. The coal combustion process is modelled as a four-stage process: 1) preheating; 2) devolatilization of raw coal, modelled using the two-competing model; 3) gaseous combustion, modelled using the eddy dissipation model; 4) the oxidation and gasification of residual char, modelled using the Gibb model. As reported elsewhere, the model has been validated against the experimental measurements for two different test rigs, respectively obtained by Mathieson et al. and Rogers.

3. Simulation Conditions

The model geometry and simulation conditions are configured based on a pilot-scale test rig used in BHP Billiton’s Newcastle Laboratories. The hot blast passes down a duct section, through the restriction of a tuyere and subsequently expands and is injected with pulverized coal into a tubular combustion test section. In order to simulate the coal combustion in PCI operation, additional features for the lance arrangement/structure and boundary conditions are considered (Table 1). This geometry provides a realistic reproduction of the flow and thermo-chemical phenomena associated with the pulverized coal combustion for a blast furnace tuyere-raceway. Based on the test rig, the numerical model geometry is designed as shown in Fig. 3. The lance is 12.7 mm in outer diameter (1.6 mm thick) with a coaxial shroud of 19.05 mm in outer diameter (1.6 mm thick).

To investigate the effect of particle size on coal burnout, a Rosin–Rammler distribution is used to describe the particle size distribution of coal. The mass fraction, \( R \), above a given particle diameter, \( d \), is calculated according to,

\[
R = \exp[-(d/d_v)^{\gamma}]..........................(1)
\]

where the Rosin–Rammler size, \( d_v \), is a measure of the fineness, and the parameter, \( \gamma \), is a measure of size dispersion. The value of \( \gamma \) for pulverized fuels is set to 1.0. Typical operational conditions used for improving burnout are investigated, including coal properties (coal particle size, coal type) and operating conditions (blast temperature, oxygen enrichment, coal rate), as listed in Table 2. Some extreme values are also tested for trial purpose. The base
values are underlined. The effect of one specific parameter is quantified by fixing the others at their base values. The final burnout level is determined at a distance of 925 mm from the lance tip.

4. Results and Discussion

In this section, the effects of some key variables on coal combustion characteristics are reported, in terms of burnout, volatile matter (VM), temperature field, and oxygen distribution. The burnout \(B\) is calculated according to the ash balance:

\[
\text{Burnout} = \left(1 - \frac{m_{a,0}}{m_a}\right) \left(1 - m_{a,0}\right)
\]

where \(m_{a,0}\) is the ash content of the raw coal and \(m_a\) is the ash content of the residual. As defined, coal burnout represents the total weight loss of the organic fraction of the coal. The key variables investigated include particle size distribution, coal type, blast temperature, oxygen enrichment and coal rate. The calculation conditions for these variables are listed in Tables 1 and 2.

4.1. Particle Size Distribution

It is difficult to experimentally explore the behaviour of particles of different sizes in a given coal. Few such numerical studies were found in the literature. In this study, this behaviour is numerically investigated.

Taking the base case \((d_e=50\ \mu m)\) as an example, Fig. 4 shows the evolutions of coal combustion characteristics with the distance from the lance tip for different size groups. A strong dependence on particle size is found for each size group. Figure 4(a) compares the volatile release of different size groups, followed by the earlier release of VM at faster rates. This is because fine particles have higher surface area/mass ratios, leading to faster temperature rises. Since coal particles start to devolatilize at approximately the same temperature for all particle sizes, the devolatilization process is delayed for large particles. As a result, fine particles require shorter preheating stages.

Figure 4(b) compares burnout evolutions as a function of the distance from the lance tip for various particle size groups. For each specific size group, a sudden transition in burnout occurs, from a rapid increase (upstream) to a plateau (downstream). Moreover, when comparing this with Fig. 4(a), these transitional zones are found to correspond to the start points of rapid drops in VM for each size group. Thus, these transition zones of sudden changes can be considered to be the ignition points of the coal particles. When comparing the burnout evolutions of various size groups, it is found that the increasing rate in the upstream and the final level in the downstream both strongly depend on particle size. Before the ignition points, i.e. in the upstream, where the devolatilization is controlling, fine particles start to burn earlier, then combust faster and reach earlier ignition points than coarse particles. This is consistent with the devolatilization evolutions of various size groups (Fig. 4(a)). However, beyond the ignition points, i.e. in the downstream, where char oxidation/gasification reactions are controlling, the burnouts of fine particles are raised to higher levels than coarse particles, because of higher surface area/mass ratios and hence higher reaction rates. As such, different burnout levels are achieved for different size groups. Therefore, for a given coal, the burnouts of fine particles increase at faster rates, and are finally raised to higher levels than large particles.

Figure 4 suggests the burnout evolution of different sized particles in the downstream. The results are sensitive to particle sizes, more sensitive than those predicted by a previously-published model (Fig. 5).\(^{21}\) As discussed elsewhere,\(^{13}\) the current model should be more acceptable in view of its more comprehension in model formulation. However, this view should be confirmed against experimental measurements, which may be done in the future studies.

To clarify the contributions of VM and char to the overall
burnout for various particle size groups, the burnout evolutions in Fig. 4(b) are further analysed in Fig. 4(c) as a function of particle size groups. For each curve in Fig. 4(b), the contribution of char reactions to the overall burnout is regarded to start at the distance where devolatilization finishes (Fig. 4(a)). That is, within this distance, the burnout increases mainly due to the VM release/combustion, whereas beyond this distance, the burnout increases mainly due to char reactions. It is evident that the burnout levels along the central plume of all size groups are determined by a combination of devolatilization in the upstream and char oxidation/gasification in the downstream, with devolatilization being the main contributor to the coal burnout level, for both fine and coarse particles. The contributions of VM are nearly the same for various size groups since the volatiles are released entirely for all size groups (Fig. 4(a)) due to the high heating rate. However, the contribution of char reactions to burnout level varies depending on particle size groups, higher for fine particles. This is because higher surface area/mass ratios of fine char particles result in higher reaction rates and diffusion rates and then greater contributions, compared with coarse particles.

Secondly, the effect of particle mean size on coal burnout is investigated, using six different Rosin–Rammler mean sizes, \(d_e\) (Table 2). Figure 6 shows the particle size distributions investigated (a), and the effect of \(d_e\) on final burnout (b). As \(d_e\) increases from 20 to 200 \(\mu m\), the burnout decreases significantly, from ~85\% to as low as ~50\%, the devolatilization is delayed (Fig. 7(a)), and oxygen consumption also becomes less (Fig. 7(b)). Moreover, it is found that the coal burnout decreases almost linearly with \(d_e\). The correlation formulated can be used as the first approximation for predicting the burnout behaviour of various coal grinds.

4.2. Coal Type

In order to examine the effect of coal type on coal burnout, four coals with different VM contents (10\%, 20\%, 32.5\% and 40\%) are investigated (Table 2), with different Q-factors assigned. Figure 8 shows the effect of coal type on final burnout. It is shown that the burnout increases with VM content. A quantified relationship is formulated, which is useful in examining potential coals in terms of burnout prior to plant trials.

The effect of coal type on some combustion characteristics are also investigated in Fig. 9, including temperature distribution (a), oxygen concentration (b) and VM content along centre line (c), respectively, so as to understand the underlying mechanisms. The results show that a higher volatile coal produces an overall higher temperature field due to stronger volatile combustion (Fig. 9(a)). As VM of coal increases, the local oxygen-deficient zone, i.e., primary reaction region moves back towards the tuyere (Fig. 9(b)); the high temperature zone also moves back towards the tuyere. On the other hand, the VM content along the centre line is specified, as illustrated in Fig. 9(c): the high volatile coal starts to release volatiles at a higher initial level, with a shorter preheating stage, followed by a faster rate of decrease, reaching the similar level as the low volatile coal at the distance of around 0.4 m. The stronger devolatilization of higher volatile coals results in a higher overall burnout level. Then the four curves intersect at around 0.4 m. Beyond this point, the decreases of VM content are all insignificant for various coals. Hence, on the whole, a high volatile coal will lead to a more rapid devolatilization and faster gaseous fuel combustion. In practice, this suggests that injecting a high volatile coal would be favoured due to improved coal combustion efficiency; a low volatile coal would require blending with high volatile coals or higher oxygen enrichment levels.

4.3. Blast Temperature

Figure 10 shows the effect of blast temperature on coal burnout at the distances of 300 mm and 925 mm from the lance tip, respectively. It is indicated that as the blast temperature increases from 800 to 1200°C, burnouts at both 300 mm and 925 mm increase significantly. However, as temperature increases above 1200°C, the burnout at 300 mm continues to increase, while the burnout at 925 mm starts to flatten. That is, the introduction of a higher temper-
ature blast affects coal burnout evolution more significantly in the upstream (i.e., near the tuyere), compared to downstream in the test rig. This indicates that it is necessary to include raceway region in the study of effects of variables. That is, if the downstream (i.e. raceway region) is not included in the simulation, some conclusions could be misleading. This can be applied to both numerical and experimental studies. On the other hand, the profiles of coal burnouts at the distance of both 300 mm and 925 mm increase quickly below 1 200°C and slowly above 1 200°C. Therefore, a blast temperature of approximately 1 200°C (typical of most present-day blast furnace operations) is considered satisfactory from the view point of coal combustion efficiency. That is, further increase in blast temperature plays a limited role in further improving burnout. This finding is also confirmed by observations in pilot scale experimental studies, but with little effort to understand the underlying mechanism.

This numerical study can be used to explain this observation. Figure 11 shows the effect of blast temperature on VM evolution (a) and oxygen concentration (b). The primary reaction zone is profiled by an oxygen mass fraction of less than 0.1. It is shown that as blast temperature increases, the coal plume undergoes a shorter preheating stage, followed by a faster rate of volatile release. The volatile release has not been completed yet under blast temperature of 800°C, whereas the VM contents are reduced to zero under blast temperatures of 1 000°C and 1 600°C (Fig. 11(a)). On the other hand, when the blast temperature increases from 800 to 1 000°C, the primary reaction zone moves closer to the tuyere; when blast temperature increases from 1 000°C to 1 600°C, the oxygen depletion con-
tours are similar in the downstream, but quite different in the upstream (Fig. 11(b)).

4.4. Oxygen Enrichment

The influence of oxygen enrichment on coal combustion is investigated by setting different oxygen concentration in the blast stream, as listed in Table 2. Figure 12 shows the influence of oxygen enrichment on final burnout. The final burnout is improved as more oxygen is added into the blast (Fig. 12), which is consistent with experimental observation. However, it was reported by Du et al. that predicted coal burnout was insensitive to oxygen enrichment, where the raceway region was not included in the simulation. Similar to the conclusion from the effect of blast temperature, it also indicates that it is necessary to consider the raceway region when investigating the effects of variables on coal burnout.

In order to understand the underlying mechanism of this improvement, the effect of oxygen enrichment on oxygen concentration (a) and temperature field (b) is investigated, as illustrated in Fig. 13. It is indicated that compared with the base case, 14% oxygen addition into the blast (i.e., oxygen concentration is 35%) provides sufficient oxygen supply for both the central coal plume and recirculating fine
particles in the peripheral region (Fig. 13(a)). Figures 13(a) and 13(b) also indicate that the use of oxygen enrichment moves the location of the most intense temperatures and chemical reactions zone back closer to the tuyeres. At high oxygen enrichment levels, sufficient oxygen is available, even within the coal plume. As a result the contacting chance of oxygen with coal is enhanced, leading to high burnout levels. Clearly, the local oxygen supply is important for high coal burnout in the raceway, which can be realized by two methods. First, oxygen enrichment in the blast is an effective way to achieve high local oxygen supply, as discussed above. Another method to increase local oxygen supply is to enhance the dispersion of coal particles in the gas phase and thus increase their contacting chance with oxygen. This can be achieved by, for example, optimizing lance design and arrangement.11)

On the other hand, in blast furnace operations, as coal rate increases, the flame temperature will decrease (see Sec. 4.5). It is found in Fig. 13(b) that oxygen enrichment generates a high gas temperature field in the chamber, with the temperature reaching nearly 3 000 K at 14% oxygen addition under the test rig conditions. Therefore, oxygen enrichment is also an effective way to maintain the desired flame temperature within the raceway.

4.5. Coal Rate

The ultimate purpose of PCI technology is to burn more coal in the raceway by optimizing various operational parameters in addition to improvements in equipment. To examine the influence of increasing coal rate on coal combustion, seven different coal rates are investigated, ranging from 15 to 60 kg/h (equivalent to 60 to 185 kg/tHM of PCI rate in practice), as listed in Table 2. Figure 14 shows the effect of coal rate on final burnout. Figure 14 indicates that as the coal rate increases up to 60 kg/h, equivalent to PCI rate of ~185 kg/t-HM, the burnout decreases significantly to as low as 65%. In addition, an approximate linear relationship is formulated between coal rate and burnout in this range of coal rate. This quantitative relationship can be used to predict coal burnout under an unidentified coal rate before the practice.

Figure 15 shows the effect of coal rate on oxygen concentration (a) and temperature field (b). It is found that as coal rate increases, the overall oxygen concentration becomes lower (Fig. 15(a)). That is, the availability of local oxygen in the gas phase becomes less. Figure 15(b) indicates that higher coal rates into the chamber can lead to a lower temperature upstream but a higher temperature downstream, as a result of the additional fuel supplied. In practice, the consequence of a lower burnout is more concerned because the resultant low permeability could lead to unstable operation of whole blast furnace.

5. Conclusions

The effects of some key variables in PCI operation, e.g. coal properties and blast conditions, on coal combustion behaviours have been studied by means of a three-dimensional model recently developed.13) The following conclusions can be drawn from this study:

(1) It is confirmed that notable improvements in combustion efficiency can be achieved when using coals with more fine particles and high VM, and oxygen enrichment. Increasing blast temperature can improve the burnout, however further increase in blast temperature over 1 200°C plays a limited role in improving burnout. Some quantitative relationships between burnout and these variables have been formulated based on the numerical results for predictive purposes in practice.

(2) These improvements are further analysed in terms of VM content, temperature field and oxygen distribution, so that the underlying mechanisms of some improvements are explored. It is indicated that for a given coal (i.e. when coal properties are fixed), devolatilization process and local oxygen availability are dominant factors for coal burnout:

• Fine particles undertake stronger devolatilization and higher availability to oxygen, and therefore reach higher burnouts;

• High VM coal gives a stronger devolatilization and therefore reaches a higher burnout;

• As blast temperature increases over 1 200°C, the devolatilization processes have been completed within a short distance in the tuyere. Consequently, the burnouts reach the similar levels at the end of the raceway;

• As oxygen enrichment increases, sufficient oxygen is available overall, even inside the coal plume, which improves the burnout;

• As coal rate increases, the oxygen concentration becomes lower, leading to a decrease in coal burnout.

(3) Coal gasification and combustion is a complicated process. A too confined set-up for physical or numerical experimentation may not be able to generate a full picture about this process. The present results suggest that it is necessary to consider the raceway region when investigating the effects of variables on coal burnout.

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