Simulation Study on Performance of Novel Oxygen-coal Lances for Pulverized Coal Combustion in Blast Furnace Tuyere

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Abstract

Pulverized coal injection (PCI) into blast furnace tuyere using two novel oxygen-coal lances has been designed by MCC Company. In this paper, a three-dimensional multi-phase model with Discrete Particle Model (DPM) approach has been developed to examine the performance of the novel oxygen-coal lance for PCI operation. Simulation conditions and properties of the PCI were obtained from the real operation conditions of the blast furnace of 580 m\textsuperscript{3} with molten iron output of 1775 t/d in the industrial experimental base of MCC Incorporation. The simulation results of novel PCI style were also compared with the results of traditional one. Results show PCI using sing coal lance and single oxygen lance pattern is inferior to the conventional PCI mode. Its disadvantages include low BR increase, poor oxygen utilization level and potential damages to the tuyere. PCI using twin oxygen-coal lances is superior to the conventional PCI pattern. Its advantages include doubled burnout ratio, satisfying oxygen consumption level in the raceway and high temperature zone in a safe distance from the nozzle.

Keywords: Pulverized coal injection; Combustion; Coal-oxygen lance; Blast furnace

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| Symbol | Description |
|--------|-------------|
| A      | area, m²    |
| C_p   | heat capacity, J/(kg·K) |
| d      | diameter, m |
| H      | total enthalpy, J/kg |
| h      | heat transfer coefficient, W/m·K |
| k      | reaction rate constant, m/s; turbulent kinetic energy, J/kg |
| M      | molar weight, kg/mol |
| m      | mass, kg |
| Δm    | produced or consumed mass, kg |
| n      | number of particles passing the cell per second |
| P      | pressure, Pa |
| Pr    | Prandtl number, dimensionless |
| Nu    | Nusselt number, dimensionless |
| Q      | heat, J |
| r      | chemical reaction rate, kmol/(m³·s) |
| Re    | Renold number, dimensionless |
| S      | source, units vary |
| Sc    | Schemit number, dimensionless |
| T      | temperature, K |
| V      | volume, m³ |
| u      | x-direction velocity component, m/s |
| v      | y-direction velocity component, m/s |
| w      | w-direction velocity component, m/s |
| y      | mass fraction, dimensionless |

**Vector**

| Symbol | Description |
|--------|-------------|
| F      | force vector |
| U      | velocity vector |

**Greek letters**

| Symbol | Description |
|--------|-------------|
| φ      | dependent variables |
| Γ      | diffusion coefficient of variable φ |
| λ      | thermal conductivity, W/(m·K) |
| ε      | turbulent dissipation rate, m²/s³ |
| μ      | fluid viscosity, kg/(s·m) |
| ρ      | density, kg/m³ |

**Subscripts**

| Symbol | Description |
|--------|-------------|
| x      | x directional component |
| y      | y directional component |
| z      | z directional component |
| i      | assigned chemical reaction |
| g      | gas phase variable |
| p      | particle variable |
1. Introduction

Pulverised coal injection (PCI) is widely adopted for cost-effective blast furnaces (BF) iron making and becomes a key step for optimizing BF iron making.[1] In conventional PCI operation, Pulverised coal (PC) are supplied to the hot blast by a simple coal lance and they are mixed in the blowpipe of the tuyere. Presently the PCI rate is on the level of 100-200 kg-coal/tHM and it’s very difficult to further increase PCI rate as industrial practises demonstrate that, by conventional PCI, PC combustion efficiency drops quickly if PCI rate increases to higher than 200 kg-coal/tHM.[2,3] Therefore how to improve the PCI rate without the reduction of PC combustion efficiency in BF has become a prime concern for BF engineers.

In general, PC combustion nearby the tuyere involves the knowledge of chemically reactive flow. It is influenced by many important BF operating parameters as blast parameters, coal type, BF operation pressure and so on.[4] Nowadays most of these parameters are close to their limits and could not be adjusted in a wide range due to the capacity of equipment or the cost considerations. Industrial practices indicate that when PCI rate is less than 200 kg-coal/tHM. PC combustion efficiency could be improved by increasing blast temperature or increasing oxygen level in the blast; however, when PCI rate is more than 200kg-coal/tHM, PC-oxygen mixing level and style become the significant factors. Several modelling works on different PCI patterns have been reported. Liu[5] reported that PC combustion could be highly intensified by introducing pure oxygen near the coal-lance tip; Du[6,7] reported that, in case that PC is supplied to the blast by two twin coal-lances other than one single coal-lance, its combustion efficiency could be increased. It is, therefore, indicated to change the injection pattern of PC could be a promising method.

In order to increase PC combustion efficiency, according to the real operation of a blast furnace at the industrial base of MCC Company, MCC Company and University of USTB have jointly developed several PCI patterns by adoption of novel oxygen-coal lances recently. The present work aims is intended to evaluate PC combustion nearby the tuyere by means of a numerical simulation. From these evaluations, the results will be adopted as potential measures to enhance PC combustion in BF in the future.

2. Description of PCI process

When PC particles are injected by carrier gas (N₂, 1kg N₂/20kg PC) from the lance end into the blowpipe of the nozzle in a continuous operation, the PC particles get dispersed due to turbulent nature of the hot blast and they reach the raceway by a projectile path under the influence of drag force and gravity. While they are traversing the projectile path, the coal particles get heated up and start releasing volatiles which then undergo homogeneous combustion and the PC particles undergo heterogeneous combustion depending upon the availability of oxygen in the hot blast. Hence they provide both heat and carbon source in BF iron making. The model geometry of the investigated nozzle is based on an engineering design of MCC Company for the BF of 580 m³ with an output of 1775tHM/day. Its schematic diagram and major specification are shown in Fig. 1. Specification of the cross section of the designed coal-oxygen lance is shown in Fig.1 as well.
3. Mathematical model

3.1. Governing equations

The simulation of PCI process in tuyere and its nearby region is based on the comprehensive representation of the features of gas phase fluid dynamics, PC injection, combustion, heat transfer including radiation and chemical reactions to investigate the velocity profile, temperature and emissions at various locations in a nozzle and its nearby region. It is based on the numerical solution of three-dimensional differential equations for conservation of mass, momentum and energy for both gas and PC phases. The gas phase is treated as a continuous phase; its general governing equation is Eq.(1) and details of Eq.(1) are listed in Table 1. The PC phase consisted of injected coal particles is solved using particle transport model where a representative number of particles are tracked through the computational domain in a Lagrangian way and the details are listed in Table 2. The two phases are coupled through momentum interaction (drag) and energy interphase interaction (heterogeneous combustion and heat transfer). Full coupling of mass, momentum and energy of particles with the gas phase are carried out. Considering the operation of PCI, when the coal particles are heated, volatile matters will be released to react with oxygen, resulting in diffusion flame combustion. The combustion therefore mainly includes the following reactions[6]: coal devolatilization, volatile combustion, char reactions. At the same time, gaseous combustion of CO is considered as well. The devolatilization process is modeled by the single step model and the volatile combustion, char reactions and gas combustion process are modeled by the eddy break-up model. All the reaction rates follow Arrhenius formula and are summarized in Table 3.

\[ \text{div}(\rho \vec{U} \Phi) = \text{div}(\Gamma \text{grad} \Phi) + S \]  \hspace{1cm} (1)

3.2. Simulation conditions

The governing equations are solved using the commercial CFD software FLUENT(V6.3.26) and our own UDF. A residual value of 1.0e-5 is used as the convergence criterion for mass-momentum equations in all simulations. DPM is used to track the coal particles which interact with the continuous gas phase flow. Unstructured tetrahedral finite volume mesh was generated as shown in Fig. 2. The number of grid is 283471 with the maximum grid volume of 3.38e-5m³. Combustion zone of coal particles after leaving the nozzle in the BF is considered to be a cylinder shape and its dimension is given in Fig.2. Wall temperature of the zone in BF is fixed to be 1973K. The operation pressure is 3.0e5pa.
Table 1. Terms used in Eq. (1) for the gas phase.

| Equation | $\Phi$ | $\Gamma$ | $S$ |
|----------|--------|--------|-----|
| Mass     | $u_g$  | $\mu_{\text{eff}}$ | $\sum_{i_p} \Delta m_{p,i} / V_{\text{cell}}$ |
| Momentum | $u_g$  | $\mu_{\text{eff}}$ | $-\frac{\partial P}{\partial x} + S_x + \sum_{i_p} F_{D,i} \Delta t / V_{\text{cell}}$ |
|          | $v_g$  | $\mu_{\text{eff}}$ | $-\frac{\partial P}{\partial y} + S_y + \sum_{i_p} F_{D,y} \Delta t / V_{\text{cell}}$ |
|          | $w_g$  | $\mu_{\text{eff}}$ | $-\frac{\partial P}{\partial z} + S_z + \sum_{i_p} F_{D,z} \Delta t / V_{\text{cell}}$ |
| Turbulent kinetic energy | $k$ | $\mu_{\text{eff}} + \frac{\mu_k}{\sigma_k}$ | $G_k - \rho_g \varepsilon$ |
| Turbulent dissipation rate | $\varepsilon$ | $\mu_{\text{eff}} + \frac{\mu_{\varepsilon}}{\sigma_{\varepsilon}}$ | $\frac{\varepsilon}{k} (C_{\varepsilon} G_k - C_{\varepsilon} \rho_g \varepsilon)$ |
| Energy   | $H_g$  | $\mu_{\text{eff}} / Pr$ | $\sum_{i_p} Q / V_{\text{cell}} - \Delta H_{f,i} r_3 - \Delta H_{g,i} r_6$ |
|          | $y_{\text{VM}}$ | $\mu_{\text{eff}} / Sc$ | $\sum_{i_p} \Delta m_{\text{VM}} / V_{\text{cell}} r_3$ |
|          | $y_{H2O}$ | $\mu_{\text{eff}} / Sc$ | $1.5 M_{H2O} / V_{\text{cell}} r_3$ |
| Species  | $y_{CO}$ | $\mu_{\text{eff}} / Sc$ | $\sum_{i_p} \Delta m_{CO} / V_{\text{cell}} r_3$ |
|          | $y_{O_2}$ | $\mu_{\text{eff}} / Sc$ | $\sum_{i_p} \Delta m_{O_2} / V_{\text{cell}} r_3$ |
|          | $y_{CO_2}$ | $\mu_{\text{eff}} / Sc$ | $\sum_{i_p} \Delta m_{CO_2} / V_{\text{cell}} r_3$ |

Table 2. Equations for the PC phase.

| Equation | $\Phi$ | $\Gamma$ | $S$ |
|----------|--------|--------|-----|
| Mass     | \( \frac{dm_{\text{p}}}{dt} = -r_1 - (r_2 + r_3 + r_4) M_C \) |
| Momentum | \( m_p \frac{dU_p}{dt} = F_D + m_{\text{g}} \) |
|          | \( F_D = \frac{1}{8} \mu_p C_p [U - U_T] (U - U_T) \), \( C_D = \max( 24(1 + 0.15 \text{Re}^{0.84}) / \text{Re}, 0.44) \) |
| Energy   | \( m_p C_p \frac{dT_p}{dt} = h_A (T_T - T_p) + \sum_{i = 1}^{4} (-\Delta H_{\text{mac}}) y_i + A_{\varepsilon \text{eff}} \sigma_{\text{P}} (T_T - T_P^4) \); |
Table 3. Chemical reactions involved in the model.

| No. | Reaction                  | Reaction Rate Expression                                      |
|-----|---------------------------|----------------------------------------------------------------|
| 1   | Coal=VM+char              | $r_i = -k_i \left[ \frac{m_{p,0}}{m_{p}} \left( 1 - f_{v,0} \right) \left( 1 - f_{v,0} \right) m_{p,0} \right]$, $k_i = 3.75 \times 10^6 \exp \left( -\frac{7.336 \times 10^4}{RT_p} \right) \text{ (kg/s)}$ |
| 2   | 2C+O$_2$=2CO              | $r_i = -2\pi d_p^2 \rho_p^2 \frac{RT_p y_{O_2}}{M_{O_2}} \frac{D_{b,k}}{D_{b} + k_i}$, $k_i = 1.813 \times 10^7 \exp \left( -\frac{1.089 \times 10^7}{RT} \right) \text{ (kmol/s)}$ |
|     | C+O$_2$=CO$_2$            | $D_{b} = \frac{D_{inf}}{T_{p} + T_{ref} \exp \left( -\frac{P_{inf}}{P_{ref}} \right) }$, $k_i = 1.225 \times 10^8 \exp \left( \frac{9.977 \times 10^3}{RT} \right)$ |
| 3   | C+CO$_2$=2CO              | $P_0 = 1.05 \times 10^4 \text{ Pa}, T_{ref} = 298 \text{ K}$, $k_i = 7.351 \times 10^6 \exp \left( -\frac{1.380 \times 10^7}{RT} \right)$ |
|     | Gaseous Combustion        | $r_{\text{mix}} = 2.11 \times 10^7 \exp \left( \frac{-2.02 \times 10^7}{RT} \right) (\rho_{a} y_{VM})^2 (\rho_{a} y_{O_2})^{0.2}$ (kg/m$^3$·s) |
| 5   | VM+1.7O$_2$=CO$_2$+1.5H$_2$O | $r_{\text{BU}} = 4.0 \rho_p \frac{y_{CO}}{k} \min \left( y_{CO}, y_{O_2} \right) \frac{1}{1.70}$ |
|     | $r_5 = \min(\rho_{a}, r_{\text{BU}})$ | $r_{\text{BU}} = 4.0 \rho_p \frac{y_{CO}}{k} \min \left( y_{CO}, y_{O_2} \right)$ (kg/m$^3$·s) |
| 6   | 2CO+O$_2$=2CO$_2$         | $r_{\text{BU}} = 4.0 \rho_p \frac{y_{CO}}{k} \min \left( y_{CO}, y_{O_2} \right)$ |
|     | $r_5 = \min(\rho_{a}, r_{\text{BU}})$ |

Fig.2 Placement of computational grid.

4. Results and discussion

PC for this research has an average size of 0.080mm and its chemical composition is 78.5 % (ad) of fixed carbon, 10% (ad) of ash, 10% (ad) of volatile and 1.5% of moisture. Three coal injection patterns were examined. The
operation parameters are listed in Table. 4. Operation data of the base case (Case A) is given in accordance with the typical running conditions of the BF in MCC industrial base. The base case was also used for model validation. The operation conditions of cases B and C are provided by MCC Company on the basis of BF iron making design.

As the measurements of in-furnace thermal and chemical properties are very difficult, only combustion temperature at the outlet of the tuyere is available for validating. The measured gas temperature in the raceway is 2300K and the temperature predicted using the model is 2200K. The model validity could then be confirmed.

In the following discussion, combustion characteristic of PC, oxygen concentration profile and gas temperature profile will be examined as they could provide fundamental information for design of tuyere and coal-oxygen lances. The horizontal plane across the tuyere axis is selected for analyzing.

### Table 4. Simulation conditions.

| Case   | Hot blast temperature (K) | O₂ supply in hot blast (Nm³/s) | N₂ supply in hot blast (Nm³/s) | O₂ supply in oxygen lance (Nm³/s) | PC supply in coal lance (kg/s) | Carrier gas in coal lance (kg/s) |
|--------|---------------------------|-------------------------------|-------------------------------|----------------------------------|--------------------------------|---------------------------------|
| Case A (Base case) | 1423                      | 0.350                         | 0.99                          | 0.0                              | 0.257                          | 0.01                            |
| Case B  | 1473                      | 0.330                         | 0.790                         | 0.060                            | 0.400                          | 0.02                            |
| Case C  | 1473                      | 0.330                         | 0.790                         | 0.030                            | 0.200                          | 0.01                            |

*Case A: Single coal lance (7% oxygen enrichment, 1775tHM/day, conventional PCI), Case B: single coal lance and single oxygen lance (15% oxygen enrichment, 1856tHM/day), Case C: Twin oxygen-coal lances (15% oxygen enrichment, 1856tHM/day).*

4.1. Trajectories and combustion of coal particles

Fig. 3 displays trajectories of PC particles for the three cases. In the conventional PCI pattern (Case A), trajectories of coal particles are nearly along the axis of the nozzle after they leave the lance tip though the coal lance is installed at an inclination angle of 12 degree to the axis. This is due to that, in this case, PCI rate is on the normal level of some 200 kg-coal/tHM, and therefore PC particles could be dispersed in the hot blast in a very short flying distance, which is some 10 cm from the lance tip as shown in Fig. 3; the trajectories of dispersed PC particles are then to be adjusted to be nearly along the nozzle axis under the drag force. In case B, particles flowing behavior are quite different from that in Case A. It could be seen in Fig.3 that, PC particles start to disperse until the particles reach the tuyere outlet (20cm from the lance tip), and moreover their trajectories are deviated severely from the nozzle axis and are inclining to the oxygen lance side. Obviously it indicates that momentum transfer from hot blast is not enough to adjust their trajectories to be along the tuyere axis. PC flow inclining to the tuyere edge is not expected in BF iron making as this could cause friction damage to the tuyere. In Case C, because PC particles are supplied by two coal-oxygen lances installed symmetrically to the tuyere axis, PC particles could fly along the axis even better than in Case A.

To determine performances of the novel oxygen-coal lances, a parameter of burnout ratio (BR) of PC is evaluated. BR is defined as the ratio of PC mass loss at the specified flying time to the original PC combustible mass at the inlet. BR variations of typical PC particles for different cases are shown Fig. 4. It could be seen that, ignition time of the PC particle is delayed as room temperature oxygen is introduced near the lance tip and PCI rate increases in Cases B and C. In the base case, coal particles start to devolatize at the flying time of 0.008s, however, in cases B and C, it takes place at some 0.010s. Moreover, PCI residence time of the base case is 0.040s and those of Cases B and C vary from 0.045s to 0.050s, which are elongated. This mainly attributed to the reduction of hot blast supply and introducing room temperature oxygen in Cases B and C. Fig. 4 shows that applying coal-oxygen lances could improve PC BR. Compared to the base case, final BR increase is 0.08 in case B and 0.20 in Case C. As regarding to the final BR, PCI pattern in Case C is the best.

4.2. Oxygen concentration profile

Intuitively, PC combustion in tuyere and raceway depends on environmental oxygen concentration. Cases B and C are intended to increase oxygen concentration around the PC flow. Simulation results of oxygen concentration
profile are given in Fig. 5. In Case A, oxygen concentration profile symmetrically to the tuyere axis and it drops from 0.20 in the tuyere to 0.10 at the raceway outlet. In Case B, PC and oxygen separate from each other from the distance of 0.8m on. As oxygen concentration is 0.40-0.20 in the coal lance side, oxygen is poorly utilized by PC there. This indicates that PCI pattern in Case B is inferior to that in Case A. In Case C, oxygen presents a similar profile as in Case A. oxygen concentration drops from 0.40 in the tuyere to 0.05 at the raceway outlet. This indicates that oxygen utilization efficiency is superior to that in Case A.

4.3. Gas temperature profile

In PCI operation, high temperature zone is expected to have a certain distance from the tuyere and temperature near the tuyere must be controlled or else the refractory of the tuyere could be destroyed. Fig.6 displays gas temperature profiles. In Case A, it shows that the max temperature is some 2200K and the hot temperature zone is some 0.2m from the tuyere outlet. Since its max temperature is not high, the distance is not significant. Max combustion temperatures of cases B and C could reach 2800K as shown in Fig 6, which is much higher than that of the Case A and indirectly indicates that the PCI operation is intensified. However, in case B, because of deviation of most PC trajectories from the tuyere axis, the hot temperature zone is in the oxygen lance side and very close to the tuyere outlet, therefore there is a potential danger to the tuyere. In Case C, the hot temperature zone in on the nozzle axis and its distance from the tuyere is 1.2m, which is a safe distance to protect the tuyere. The above comparison still shows the twin oxygen-coal lances design has the effect to push the high combustion temperature zone away from the tuyere.
Fig. 4. BR variation with PC flying time.

(A) coal lance

(B) oxygen lance coal lance

(C) oxygen-coal lance

Fig. 5. Oxygen volume fraction profile.
5. Conclusions

Performance of the conventional PCI mode and two envisaged PCI modes applying novel oxygen-coal lances have been numerically analyzed. Their results on PC combustion behavior, oxygen concentration and combustion temperature in tuyere and raceway were compared. The conclusions are: PCI using single coal lance and single oxygen lance mode is inferior to the conventional PCI mode; its disadvantages include low increase of BR, poor oxygen utilization level by PC and potential damages to the tuyere. PCI using twin oxygen-coal lances is superior to the conventional PCI mode; its advantages include doubled BR, satisfying oxygen consumption level by PC in the raceway and high temperature zone in a safe distance from the nozzle.

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