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Numerical prediction and practical improvement of pulverized coal combustion in blast furnace☆

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Abstract

The burning characteristics of pulverized coal in blowpipe and tuyere at two different injection patterns are simulated numerically, to aid improving the practical performance of blast furnace. With the condition of the same fuel and oxidant mass flow rates, the predictions indicate that the combustion efficiency of pulverized coal using double-lance can be substantially enhanced compared with that using single lance. Accordingly, the pulverized coal injection in a practical blast furnace was modified from single lance to double-lance. As a result, the practical injection rate of the pulverized coal in the blast furnace was increased from 110 to 153 kg/tHM, revealing that a profound decrease in operating cost of the blast furnace has been implemented.

Keywords: Blast furnace; Pulverized coal; Blowpipe and tuyere; Combustion; Injection

1. Introduction

It is known that coal plays an important role in energy developments and industrial applications. For example, since the industrial revolution occurred in eighteenth century [1], a considerable amount of coal has been utilized for power generation in steam engines. In the last decade of 19th century, pulverized coal (PC) began to be used in cement industry for heating drying kilns [2]. Nowadays, pulverized coal is widely applied in coal-fired power plants for producing electricity [3,4]; it is also extensively used in metallurgical industry for refining metals. As far as the process of ironmaking is concerned, conventionally, coke, the product of high-temperature pyrolysis of coal, serves as an important reactant in reducing iron ores into hot metal in blast furnaces [5]. However, because of higher price of coke compared with pulverized coal, the technique of pulverized coal injection (PCI) from tuyere has been developed for several years to partially replace the consumption of coke. In other words, the operating cost of the blast furnace can be substantially reduced if the injection rate of PC is promoted significantly.

The pulverized coal can be used as auxiliary fuel in a blast furnace and possesses the merit of reducing operating cost. Nevertheless, it should be addressed that, if coal particles in combustion zones undergo incomplete combustion, the unburned or residual char will accumulate in the blast furnace in which the char is depleted by means of reaction with slag and carbon dioxide [6,7]. If the accumulation rate of the char in the furnace is larger than the depletion rate,

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Nomenclature

A_p	Coal particle surface
C_p	Specific heat of coal particle
E	Activation energy
h	Convective heat transfer coefficient
k	Reaction rate constant or turbulent kinetic energy
m_p	Coal particle weight
t	Time
T_p	Temperature of coal particle
T_∞	Gas temperature
x_i	Spatially coordinate
Y_1, Y_2	Mass fractions of emitted volatile at low and high temperatures

Greek symbols

ε	Dissipation of turbulent kinetic energy
ε_p	Emissivity of coal particle
μ	Viscosity
σ	Stefan–Boltzmann constant ($=5.67\times10^{-8}$ W/m^2 K^4)

Subscripts

f	Fuel
o	Oxidizer
p	Coal particle
∞	Gas phase

the movement of hot blast will be retarded. This results in a pressure fluctuation which further suppresses the operation of the blast furnace. In consequence, enhancing the burning rate of PC and reducing the accumulation ratio of unburned char is one of available methods to stabilize the performance of the blast furnace.

Because the operation of PCI is highly relevant to the performance of the blast furnace, the purpose of the present study is to predict the combustion characteristics of pulverized coal in a blast furnace through numerical simulation. By varying the injection pattern of PC, its impact on the burning behaviors of the PC in the blast furnace will be evaluated. Furthermore, based on the obtained results, a practical strategy in improving PC combustion will be adopted.

2. Mathematical formulation

2.1. Burning process of pulverized coal

A schematic diagram of the internal structure of a blast furnace is demonstrated in Fig. 1. Attention of the present study is focused on the pulverized coal combustion in the regions of blowpipe and tuyere in the blast furnace. As shown in the figure, when coal particles are injected into the blowpipe, they will immediately immerse in a high-temperature environment filled with hot blast and thereby experience rapid heating, devolatilization reaction of the coal, oxidization of volatile matters with hot blast, combustion of residual unburned char, and gasification of the char. Recognizing the above characteristics, it is known that the devolatilization reaction initiates coal combustion, implying that the selection of parameters to model the devolatilization reaction is of the utmost importance in predicting the PC combustion. Therefore, in the current study, the initial chemical reaction of coal particles will be tested and verified to ensure the validity of the numerical method.

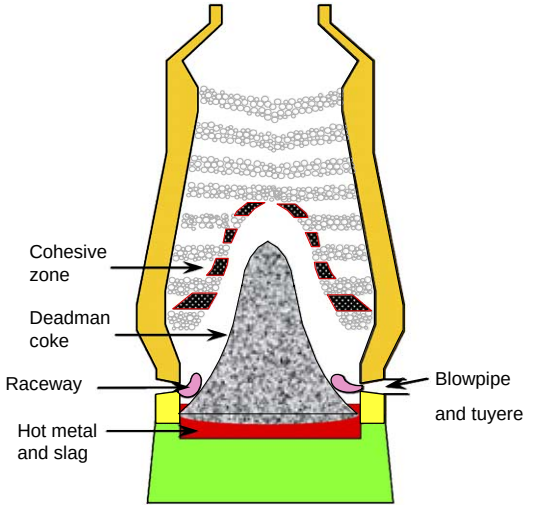

Fig. 1. A schematic diagram of internal structure in a blast furnace.

2.2. Momentum and energy balance of a coal particle

Considering a moving coal particle, when it is assumed to be spherical and the Lagrangian framework is used, the trajectory of the particle can be obtained by solving a single particle momentum equation. That is, the rate of change of momentum is equal to external forces on the particle. On account of very small coal particles investigated, it is proper to neglect body force and only drag force is considered during computation. Consequently, the equation of motion of the particle is expressed as:

$$m_{\mathrm{p}} \frac{\mathrm{d}\vec{v}_{\mathrm{p}}}{\mathrm{d}t} = \vec{F}_{\mathrm{p}} \tag{1}$$

In regard to the energy balance, with conceiving the coal particle as a lump system, the heating of the particle is carried out by convection and radiation; thus the temperature of the particle can be described by the energy equation as the following:

$$m_{\mathrm{p}} C_{\mathrm{p}} \frac{\mathrm{d}T_{\mathrm{p}}}{\mathrm{d}t} = hA_{\mathrm{p}}(T_{\infty} - T_{\mathrm{p}}) + \varepsilon_{\mathrm{p}} A_{\mathrm{p}} \sigma (T_{\infty}^4 - T_p^4) \tag{2}$$

2.3. Model of devolatilization of coal particle

When one is concerned with the devolatilization process of coal particles, it depends strongly on the heating rate, reaction time, and coal grade, and so forth. In fact, as the heating process is fast, the volatile matters emitted from the coal is larger than the analyzed result of ASTM, rendering that Q factor is larger than one. To describe the devolatilization process more realistically, two-competing devolatilization model [8] is employed. The two parallel and competing reactions are given as follows:

$$\text{coal} \xrightarrow{k_1} (1 - Y_1) \times \text{Char}_1 + Y_1 \times \text{Volatile} \quad \text{(low temperature)} \tag{3}$$

$$\text{coal} \xrightarrow{k_2} (1 - Y_2) \times \text{Char}_2 + Y_2 \times \text{Volatile} \quad \text{(high temperature)} \tag{4}$$

Furthermore, the reaction kinetics is written by:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = (k_1 Y_1 + k_2 Y_2)\text{Coal}; \quad k_1 = A_1 \exp\left(-E_1/RT_p\right) \text{ and } \quad k_2 = A_2 \exp\left(-E_2/RT_p\right) \tag{5}$$

Table 1
Operational conditions selected by Burgess et al. [11]

Reactor diameter (mm)	50
Hot blast temperature (K)	1243
Hot blast velocity (m/s)	68
Coal particle diameter (μm)	40
Volatile matter of PC (db), %	35.9
PC injection rate (kg/h)	5.3

where V and R are mass fraction of volatile matter and universal gas constant, respectively. In examining the preceding model, it is apparent that the parameters Y_1, k_1, Y_2, k_2, E_1, and E_2 have a vital influence in predicting the devolatilization process. The appropriate values will be suggested later.

2.4. Turbulent combustion model

In the gas phase the fluid motion is fast, the k–ε model is thus applied to simulate the turbulent combustion. In the operation of PCI, following the release of volatile matters from coal particles, oxygen will encompass the volatile, yielding the diffusion flame combustion. In such a situation, mass fraction probability density function (PDF) model [9] is an appropriate method to approach the reaction phenomena. The model is established based on the concepts of mixture fraction, mix-is-burnt, and probability density function. For a system just having two reactants, consisting of fuel and oxidant, the PC combustion can be approximated by a single-step reaction as:

$$1 \text{ kg Fuel} + i \text{ kg Oxidant} \rightarrow (1+i) \text{ kg Product} \tag{6}$$

The coefficient i represents the stoichiometric balance between the fuel and oxidant. When the turbulent transport coefficients of reactant and oxidant in the flow field are summed to be equivalent, employing the Zeldovich transformation the combined mass fraction X can be obtained as the following:

$$X = M_{\mathrm{f}} - M_{\mathrm{o}}/i \tag{7}$$

and the mixture fraction f is defined by:

$$f = \frac{X - X_0}{X_f - X_0} \tag{8}$$

where M_{f}, M_{o}, X_{f}, and X_0 stand for mass fractions of fuel and oxidant as well as combined mass fractions on the fuel and oxidant sides, respectively. The mixture fraction f is a conservative scalar, and its value at a control volume can be calculated via the solution of its instantaneous conservation equation for $\bar{f}$ (time-averaged):

$$\frac{\partial}{\partial t}(\rho \bar{f}) + \frac{\partial}{\partial x_i}(\rho u_i \bar{f}) = \frac{\partial}{\partial x_i}\left(\frac{\mu_{\mathrm{t}}}{\sigma_{\mathrm{t}}}\frac{\partial \bar{f}}{\partial x_i}\right) + S_{\mathrm{m}} \tag{9}$$

In the above equation, ρ, μ_{t}, x_i and S_{m} designate density (g/cm^3), dynamics viscosity (N s/m^2), spatial coordinate, and source term stemming from the reaction of coal into the gas phase, respectively. Meanwhile, σ_{t} is a computational

Table 2
Two sets of parameters used for predicting PC devolatilization

	Kobayashi et al. [9]	Ubhayakar et al. [12]
Y_1	0.3	VM
Y_2	1	$1.5 \times Y_1$
k_1 (1/s)	200,000	3.7×10^5
k_2 (1/s)	1.3×10^7	1.46×10^{13}
E_1 (kJ/mol)	1.046×10^2	74
E_2 (kJ/mol)	1.674×10^2	251

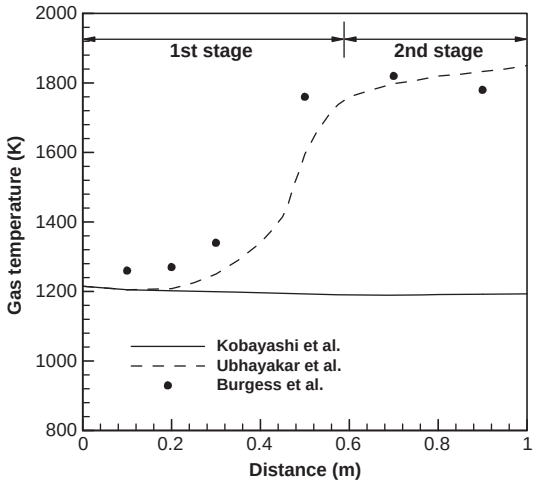

Fig. 2. A comparison of gas temperature distribution among experimental measurement and two devolatilization models.

parameter whose value is given by 0.9 [10]. In the framework of PDF, mean square value of concentration fluctuation g can be calculated through the following equation

$$\frac{\partial}{\partial t}(\rho g)+\frac{\partial}{\partial x_i}(\rho u_i g)=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_t}\frac{\partial g}{\partial x_i}\right)+C_g\mu_t\left(\frac{\partial g}{\partial x}\right)^2-C_{\mathrm{d}}\rho\frac{\varepsilon}{k}g \tag{10}$$

where C_g and C_{d} are the computational parameters and they are given by 2.8 and 2.0, respectively. According to mixture fraction f, molar fraction of each gas species, density, and temperature in control volume can be calculated.

3. Results and discussion

3.1. Numerical validation and parameter selection

Previous to simulating the physical phenomena, accurate selection of the parameters in the devolatilization model has to be carried out. To achieve this goal, the presently predicted results are compared with the experimental data of Burgess et al. [11] to confirm the validity of the simulation. The investigated conditions are summarized in Table 1. In the meantime, two sets of parameters, reported by Kobayashi et al. [9] and Ubhayakar et al. [12], are tested for comparison each other. Details of the parameters are given in Table 2 and the predicted temperature distributions in the blowpipe and tuyere are displayed in Fig. 2. It depicts that the temperature is spatially uniform when using the parameters of Kobayashi et al., implying that the devolatilization reaction in the reactor is not exhibited. Clearly, the preceding result is inconsistent with the experimental measurement. Regarding the parameters of Ubhayakar et al., as shown in Fig. 2, the predicted temperature distribution is close to the experimental data. It follows that the proposed parameters of Ubhayakar et al. is capable of providing a more realistic prediction. Because of this, their parameters are employed in the current study.

On the other hand, in examining the calculated temperature distribution, it is noteworthy that the curve is characterized by monotonic increase with increasing distance away from the lance exit. The profile can be partitioned into two stages; it composes of rapid rise in the upstream region and progressive increase in the downstream one. The behavior in the first region arises from the PC devolatilization or pyrolysis reaction followed by the combustion of the emitted volatile matters with oxygen. In regard to the

Table 3
Operating conditions of PCI in CSC

Hot blast conditions	Temperature: 1423 K; pressure: 4.5 atm; Mass-flow-rate: 3.9 kg/s; oxygen content: 21%.
Properties of PC	FC: 55.09%; VM: 35.13%; ash: 6.23%; moisture: 3.55%.
Particle distribution of PC	90 μm: 5%; 63 μm: 25%; 45 μm: 55%; 20 μm: 15%.
Others	Lance angle: 15°; lance internal diameter: 20 mm; Carrier gas mass-flow-rate: 0.026 kg/s; PC injection rate: 0.4 kg/s; heat loss of tuyere: 900,000 W/m^2.

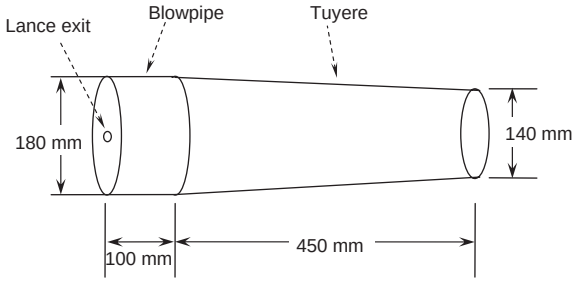

Fig. 3. A schematic diagram of blowpipe and tuyere as well as their sizes.

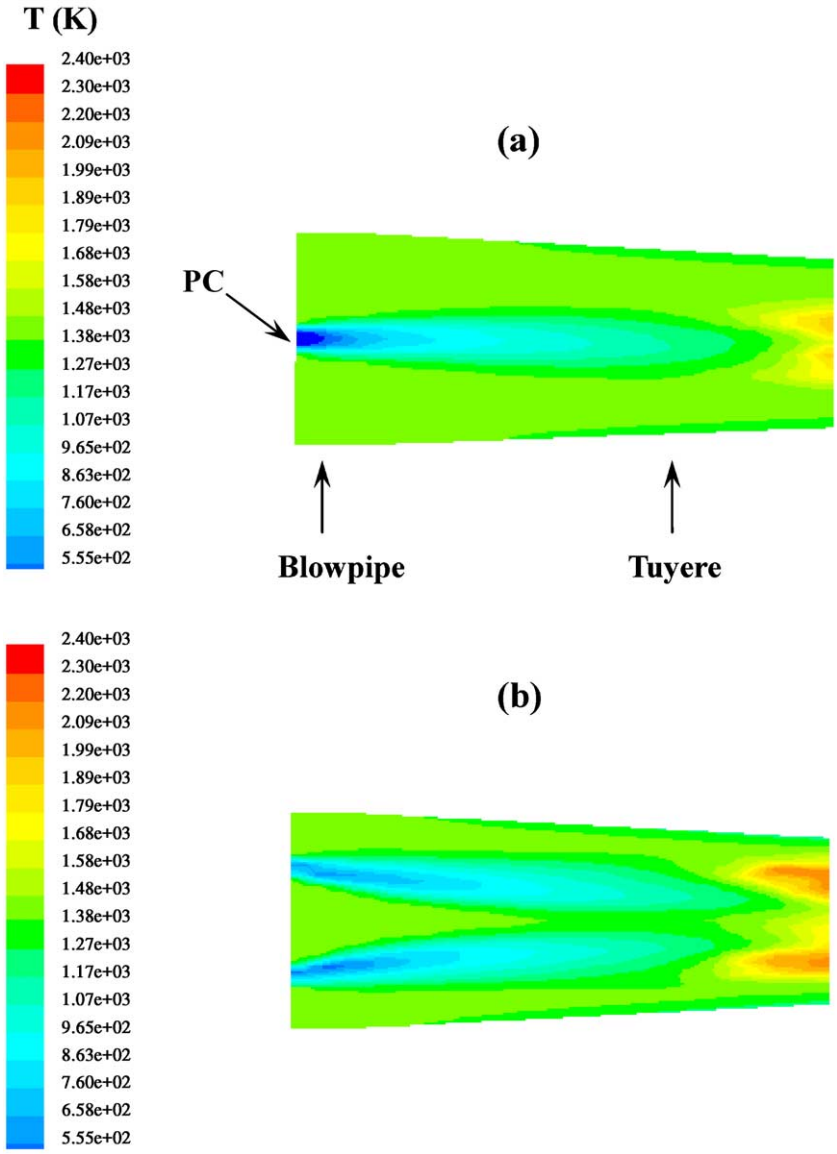

Fig. 4. Isothermal contours in blowpipe and tuyere under the operations of (a) single lance and (b) double-lance injections.

second region, the slow increase in temperature is attributed to the reaction between char and oxygen. In a word, after the PC is blown into the blowpipe, the chemical reaction is primarily achieved by the gas-phase combustion (i.e., homogeneous reaction) and then implemented by the solid-phase oxidation (i.e., heterogeneous reaction).

3.2. Impact of injection pattern

As mentioned previously, the emphasis of the present work is upon the burning characteristics of pulverized coal in blowpipe and tuyere. To evaluate the behaviors of PC combustion with different injection patterns, a typical running condition of the blast furnace in China Steel Corporation (CSC), as shown in Table 3, is simulated. Meanwhile, the physical geometries of the blowpipe and tuyere are illustrated in Fig. 3. When attention is placed on the influence of injection pattern upon the PC combustion, two different cases, consisting of single lance and double-lance, are calculated where the mass flow rates of PC and carrier gas are fixed. Accordingly, the diameters of the lances in the cases of single lance and double-lance are 20 and 14 mm, respectively. To provide a reference for indicating combustion efficiency, the burning ratio of PC is defined as:

$$\text{burning ratio } (\%) = \frac{M_e}{M_i} \times 100\% \tag{11}$$

where M_e and M_i are the PC weight-loss at the exit of tuyere and the original PC weight at the entrance of blowpipe, respectively. The calculations suggest that, once the single lance is modified to the double-lance, the burning ratio is substantially promoted from 4.9% to 12.2%. To proceed farther into the recognition of the burning mechanisms, Fig. 4 displays the isothermal contours in the blowpipe and tuyere in accordance with the performances of the single lance and the double-lance. In the both cases, because the PC and carrier gas are at room temperature prior to entering the blowpipe, the temperatures in the vicinity of the entrance are relatively lower, as observed. When comparing the isothermal contours in the downstream, it can be found that the ignition of the latter case occurs earlier than that of the former. This obviously reflects that the operation of the double-lance can facilitate the mixing between the PC and hot blast, whereby the production rate of unburned char adjacent to the exit of the tuyere is reduced.

3.3. Practical improvement of blast furnace

The aforementioned results have provided a practical insight into the performance of the blast furnace. Based on the simulations, the injection pattern in one of the blast furnaces in CSC has been the redesigned through changing the single lance to the double-lance. After that, the injection rate of PC has been promoted to a great extent, from 110 kg/tHM (ton of hot metal) to 153 kg/tHM. For this reason, the goal of reducing the operating cost of the blast furnace has been accomplished sufficiently.

4. Conclusions

By utilizing two different injection patterns of pulverized coal, the burning characteristics of the pulverized coal in the blast furnace have been examined. The numerical simulations elucidate that the performance of PCI by means of double-lance is capable of providing a superior burning, in contrast to the original single lance design. This is attributed to the fact that the double-lance injection is conducive to mixing between pulverized coal and hot blast, resulting in earlier ignition of the fuel. The practical injection pattern of the PC in the blast furnace was modified from the double-lance to the single lance, in accordance with the foregoing numerical predictions. As a result, the injection rate of the PC has been amplified by a factor of 40%, from 110 to 153 kg/tHM. In summary, the numerical study has provided a useful insight into the practical improvement of the blast furnace performance.

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