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Combustibility of biochar injected into the raceway of a blast furnace

Agung Tri Wijayanta [a,b], Md. Saiful Alam [c], Koichi Nakaso [c], Jun Fukai [c,*], Kazuya Kunitomo [d], Masakata Shimizu [d]

[a] Research and Education Center of Carbon Resources, Kyushu University, 6-1 Kasuga-koen, Kasuga, Fukuoka 816-8580, Japan
[b] Department of Mechanical Engineering, Graduate School of Engineering, Sebelas Maret University, Jl. Ir. Sutami 36 A Surakarta 57126, Indonesia
[c] Department of Chemical Engineering, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819–0395, Japan
[d] Department of Materials Process Engineering, Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

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ABSTRACT

The combustibility of Taiheiyo coal and oak char in the tuyere and raceway of an ironmaking blast furnace was simulated. The effects of injection rate, O_2 concentration and particle diameter on combustibility were studied. Numerical results showed that increasing the O_2 concentration from 23 to 27 wt.% resulted in higher combustibility of both solid fuels. However, this effect was insufficient to increase the combustibility of oak char at high injection rates because its volatile content was lower than that of Taiheiyo coal. Temperature and reaction fields were sensitive to both combustion heat and volatile content. A longer raceway or smaller particle size was required to obtain the same combustibility of biochar as of the reference coal. If Taiheiyo coal with a particle diameter of 70 μm was used at a high injection rate of 200 [(kg solid fuel)/(1000 Nm^3 feed gas)] with hot blasts containing 27 wt.% O_2, the particle diameter of oak char was required to be 60 μm to obtain the same combustibility. These predictions reveal the potential of pulverized biochar injection instead of conventional pulverized coal injection in blast furnace ironmaking.

1. Introduction

Use of carbon neutral materials sourced from biomass is a promising solution to overcome the environmental effects and continuous decrease in availability of conventional fossil fuels. Compared with coal, biomass is a solid fuel that has higher moisture and volatile content, and lower latent heat and density. Biomass can generally be defined as a hydrocarbon fuel because it mainly consists of carbon, hydrogen, oxygen and nitrogen. Carbonization of biomass increases the carbon content, removes oxygen, and the resulting biochar offers a substantial increase in energy density [1]. Biomass is considered one of the most important renewable energy sources [2–4]; however, the use and refining of biomass in the iron and steel industry are limited.

Blast furnaces are predicted to dominate global hot metal production capacity in the foreseeable future. The need exists to develop innovative ironmaking technology that considerably reduces the energy consumption and CO_2 emissions from those of current processes. Therefore, it is important to analyze the heat and mass transfer phenomena inside blast furnaces. However, it is almost impossible to obtain accurate information inside a blast furnace [5]. In a blast furnace, preheated air and solid fuel, generally pulverized coal, are injected into the lower part of the furnace through tuyere, forming a raceway in which the injected fuel and some of the coke descending from the top of the furnace are combusted and gasified. The raceway zone is primarily responsible for the production of combustion gases in the blast furnace. Mathematical models to analyze the effect of uncertain factors on the combustion characteristics of pulverized coal injected into a blast furnace have been reported [6–9]. Numerical predictions have also been reported, revealing that modifying the injection pattern from single to double lance should increase burning [10,11]. Predictions treating volatile matter as a single gas or a gas mixture gave acceptable results for final burnout [12]. The effect of coal blending has also been investigated [13]. It was necessary to adjust the blending fractions to achieve a good chemical interaction between component coals in terms of volatile content and particle temperature. The high volatile coal released more volatile matters, helping a higher gas temperature field, which then heated up the low volatile coal and promoted its devolatilization and combustion.

It is difficult to design energy strategies because of uncertainties over environmental effects and economic prospects, so good performance development planning is required. Despite much effort to reduce CO_2 emissions, it is still almost impossible to capture CO_2 from flue gases at a reasonable cost. Use of biochar in blast furnaces instead of conventional pulverized coal injection may be a way to reduce CO_2 emissions from the ironmaking process and protect the environment. This paper provides a numerical investigation of the combustion of pulverized biochar injection in blast furnace ironmaking. The purpose of this study is to investigate numerically the combustibility of biochar compared with conventional pulverized coal injected into the raceway of a blast furnace. Findings from this study are expected to contribute to understanding the feasibility of pulverized biochar injection in blast furnace ironmaking.

* Corresponding author. Tel.: +81 92 802 2744; fax: +81 92 802 2794.
E-mail address: jfukai@chem-eng.kyushu-u.ac.jp (J. Fukai).

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2. Numerical analysis

This numerical investigation simulated from the tuyere (which has a single lance for fuel and blast injection for hot gas) to the raceway region of a blast furnace. The tuyere was used to implement a hot blast and inject the solid fuel from the lance. In the blast furnace, the raceway was surrounded by a packed bed of coke. It was assumed that the raceway did not contain any solid particles like coke. Taiheiyo coal (hereafter called Taiheiyo) and oak char were used in this numerical simulation.

2.1. Mathematical model

Combustion is considered to involve the following stages: inert heating, devolatilization of solid fuel particles, gaseous combustion of volatiles, and then oxidation and gasification of char. Gas–particle flow plays a dominant role in the multiphase flow in an ironmaking blast furnace. Comprehensive continuum (Eulerian) and discrete (Lagrangian) models describing the hydrodynamics of gas-particle flow as the discrete particle model (DPM) have been developed. The DPM follows the Euler–Lagrange approach, where the gas phase is treated as a continuum and every particle is tracked individually as a discrete entity. The coupling of the DPM with a finite volume description of the gas phase based on the Navier–Stokes equations through particle–fluid interaction forces was used in this simulation.

In this model, the gas–solid flow was assumed to be at steady state. The gas phase was treated with an Eulerian frame and described by steady-state Reynolds-averaged Navier–Stokes equations closed by $k-\varepsilon$ turbulence model equations. The continuity, momentum and energy are respectively expressed as follows:

$$\nabla\cdot\left(\rho\,\vec{u}\right)=S_m, \tag{1}$$

$$\nabla\cdot\left(\rho\,\vec{u}\,\vec{u}\right)=-\nabla p+\nabla\cdot(\overline{\tau})+\rho\,\vec{g}+\vec{F}, \tag{2}$$

$$\nabla\cdot\left(\vec{u}(\rho H+p)\right)=-\nabla\cdot\left(\sum_j h_j J_j\right)+S_h. \tag{3}$$

The equation for gas species i has the following form:

$$\nabla\cdot\left(\rho\,\vec{u}\,Y_i\right)=-\nabla.\,\vec{J_i}+R_i+S_i. \tag{4}$$

Turbulence was solved using the standard $k-\varepsilon$ turbulence model [14]. The transport equations for turbulent kinetic energy k and turbulence dissipation rate ε according to the $k-\varepsilon$ model are described respectively as follows:

$$\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon-Y_M+S_k, \tag{5}$$

$$\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon, \tag{6}$$

where G_k represents the generation of turbulence kinetic energy related to the mean velocity gradient, and the turbulent model constants are $C_{1\varepsilon}=1.44$, $C_{2\varepsilon}=1.92$, $\sigma_k=1.0$, and $\sigma_\varepsilon=1.3$.

In discrete phase modeling, pulverized particles with known size distributions and properties are injected into the combustion chamber and tracked throughout the computational domain using a Lagrangian approach. The particle trajectory was solved by individually tracking each particle using Newton's second law of motion. The continuity and momentum of particles are expressed as follows:

$$\frac{dm_\mathrm{p}}{dt}=\dot{m}, \tag{7}$$

$$\frac{du_p}{dt}=F_D\left(u-u_p\right)+\frac{g\left(\rho_p-\rho\right)}{\rho_p}+F, \tag{8}$$

where F indicates the additional fluid acceleration. $F_D(u-u_p)$ represents the drag force per unit particle mass and F_D is determined from

$$F_D=\frac{18\mu}{\rho_p d_p^2}\frac{C_D\mathrm{Re}_d}{24}. \tag{9}$$

Re_d is the relative Reynolds number based on the particle diameter and relative velocity as follows:

$$\mathrm{Re}_d=\frac{\rho d_p\left|u_p-u\right|}{\mu}. \tag{10}$$

The rapid heating from the hot blast causes devolatilization in the initial period of injection. When the temperature of the coal particles reaches the vaporization temperature, devolatilization starts. The vaporization temperature is an arbitrary modeling constant used to control the onset of devolatilization. Significant devolatilization starts around 600 K [15]. The change of particle temperature is determined from the energy balance of particles governed by convective and latent heat transfer associated with mass and radiative heat transfer, respectively [16,17].

$$m_\mathrm{p}c_\mathrm{p}\frac{dT_\mathrm{p}}{dt}=h_{i,conv}A_\mathrm{p}\left(T_{\mathrm{g},i}-T_\mathrm{p}\right)+\frac{dm_\mathrm{p}}{dt}H_{reac}+A_\mathrm{p}\varepsilon_\mathrm{p}\sigma\left(T_R^4-T_\mathrm{p}^4\right) \tag{11}$$

Here, $h_{i,conv}$ is associated with the Nusselt number, which is a function of particle Reynolds number and gas Prandtl number, and is evaluated using the correlation of Ranz and Marshall [18,19] as:

$$Nu_i=\frac{h_{i,conv}d_{\mathrm{p}i}}{k_\alpha}=2.0+0.6\mathrm{Re}_d^{1/2}\mathrm{Pr}^{1/3}, \tag{12}$$

where Pr is the Prandtl number of the continuous phase,

$$\mathrm{Pr}=c_p\mu/k_\alpha. \tag{13}$$

The devolatilization process releases volatiles ($C_\alpha H_\beta O_\gamma N_\delta$) and char (C(s)).

$$\text{Solid Fuel}\rightarrow C_\alpha H_\beta O_\gamma N_\delta+C(s) \tag{R1}$$

The rate of devolatilization indicates that volatiles are released at a constant rate according to the following expression [15]:

$$-\frac{1}{f_{v,0}\left(1-f_{w,0}\right)m_{\mathrm{p},0}}\frac{dm_\mathrm{p}}{dt}=A_0. \tag{14}$$

Combustion of volatiles ($C_\alpha H_\beta O_\gamma N_\delta$) is simplistically represented by two overall gas reactions as follows:

$$C_\alpha H_\beta O_\gamma N_\delta+aO_2\rightarrow bCO+cH_2O+dN_2, \tag{R2}$$

$$CO+0.5O_2\rightarrow CO_2. \tag{R3}$$

The stoichiometric coefficients of reaction R2 are presented in Table 1. The finite rate/eddy dissipation model for the gas reaction mechanisms in turbulent flow can be used once the reaction rates of