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Burning characteristics of pulverized coal within blast furnace raceway at various injection operations and ways of oxygen enrichment

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HIGHLIGHTS

- Coal combustion behavior in blowpipe, tuyere, and raceway is examined.
- Double lance injection has better dispersion and earlier ignition of pulverized coal.
- Enriched oxygen becomes combustion enhancer in the downstream of coal plume.
- Pressure loss in the raceway under oxy-coal lance injection is lower.
- Blast furnace performance may be improved from oxy-coal lance injection.

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ABSTRACT

In this research, coal combustion behavior across the regions of blowpipe, tuyere, and raceway of blast furnace are numerically examined. Three different lance configurations, including a single lance, a double air-cooled coaxial lance, and an oxy-coal lance with different oxygen enrichment patterns, are taken into consideration. The coal combustion efficiency by the double lance injection is 5.1% higher than that by single lance injection. From the calculated temperature by the oxy-coal lance, coal ignition is retarded due to the cooling effect of enriched oxygen flowing through the lance annulus, resulting in the moderation of pressure loss within the raceway. Most importantly, the enriched oxygen becomes the combustion enhancer in the downstream of coal plume after ignition is triggered. Consequently, the coal burnout under the oxy-coal lance injection is comparative to that under the double air-cooled lance injection. The performance of blast furnace may be improved with the advantages provided by the oxy-coal lance injection. Compared with the single lance injection, coal trajectories under the oxy-coal lance injection are closer to the tuyere exit due to the higher inertia force of coal particles against hot blast. This should be taken into account for the designs of the oxy-coal lance.

1. Introduction

A number of new ironmaking processes have been developed over the last several decades; however, blast furnaces are still the most important and commonly employed facilities for hot metal production due to their superiority in productivity and heat utilization [1–3]. In order to reduce iron ore into iron, metallurgical coke is fed from the top of the blast furnace. Meanwhile, pulverized coal is injected and burned at the bottom of the furnace to provide heat for the reduction reactions [4]. On account of mass consumption of coal for hot metal production, ironmaking is an energy-intensive industry and a large amount of CO_2 is emitted into the atmosphere [5–7].

During the operation of blast furnace, blast air heated to temperatures of 1100–1250 °C is blown into the furnace through tuyeres, and reacts with coke in raceways to generate heat and reduction gases for iron ore reduction. To diminish the consumption of expensive coke, some cheaper auxiliary fuels, such as oil, natural gas, and pulverized coal, have been used as the substitutes of coke and injected through lances into raceways. Due to the relatively low price and abundant reserve of coal in comparison with other fossil fuels, nearly half of blast furnaces in the world (47.7%) use pulverized coal injection (PCI), while only 4.1% use oil, 11.9% use gas, and 0.2% use plastic injection [8]. For a stable PCI

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Nomenclature

A_p	coal particle surface (m^2)
C	coal
C_0	inertial loss coefficient (m^{-1})
C_p	specific heat of coal particle ($J\,kg^{-1}\,K^{-1}$)
C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$	empirical constants for turbulence model
D_c	coke diameter in the coke bed (m)
D_p	coal diameter (m)
E	activation energy ($kJ\,mol^{-1}$)
f	mixture fraction
f_D	drag force from a particle (N)
F	fuel
G_k	generation of turbulence kinetic energy ($kg\,m^{-1}\,s^{-3}$)
H	total enthalpy ($J\,kg^{-1}$)
h	convective heat transfer coefficient ($J\,kg^{-1}$)
k	turbulent kinetic energy ($m^2\,s^{-2}$)
k_1, k_2	devolatilization rate constant (s^{-1})
M	mass fraction
m_p	coal particle weight (kg)
O	oxidant
Q_{reac}	reaction heat ($J\,kg^{-1}$)
q	heat transfer from a particle (W)
Pr_t	turbulence Prandtl number
R	universal gas constant ($kJ\,mol^{-1}\,K^{-1}$)
S	source term ($kg\,m^{-2}\,s^{-2}$)
S_1, S_2	char
t	time (s^{-1})
T_p	temperature of coal particle (K)
T_∞	gas temperature (K)
U	mean velocity ($m\,s^{-1}$)
v	mass fraction of solid lost as volatiles
V_1, V_2	volatile released at low and high temperatures
X	combined mass fraction
x_i	spatially coordinate
Y_1, Y_2	mass fractions of emitted volatile at low and high temperatures

Greek symbols

α	porosity
α_t	empirical constants for turbulence model
ε	dissipation of turbulent kinetic energy ($m^2\,s^{-2}$)
ε_p	emissivity of coal particle
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	viscosity ($kg\,m^{-1}\,s^{-1}$)
μ_{eff}	effect viscosity of gas ($kg\,m^{-1}\,s^{-1}$)
μ_t	turbulent viscosity ($kg\,m^{-1}\,s^{-1}$)
σ	Stefan–Boltzmann constant (=$5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$)
σ_t	Prandtl number of turbulence kinetic energy
ρ	density ($kg\,m^{-3}$)

Subscripts

f	fuel
o	oxidizer
p	coal particle
g	gas phase

operation, high coal burnout along with a low pressure loss (high permeability) is always desirable in the regions of blowpipe, tuyere, and raceway. However, it is difficult to simultaneously implement the two situations because the enhancement of coal combustion intensity may raise the pressure loss of blast flow within the raceway.

China Steel Corporation (CSC) is the only integrated steel producer in Taiwan, and has four blast furnaces located in Kaohsiung and two in Taichung. For the cost reduction of fuel and its stable supply, the auxiliary fuel injected at CSC has been changed from oil to pulverized coal since 1988. In an attempt to increase PCI rate and stabilize blast furnace operation, simulation models by computational fluid dynamics (CFD) code have been developed at CSC to investigate the flow patterns of injected coal and gas temperature distributions in combustion zone. Upon inspection of the predicted trajectories of coal particles in the regions of blowpipe and tuyere [9], it was found that the dispersion of injected pulverized coal into hot blast was poor when single lance injection was operated. This resulted in relatively low combustion efficiency of coal and soot formation [10,11]. On the other hand, from the calculated temperature contours within the regions of blowpipe and tuyere [12], pulverized coal ignition could be triggered earlier under the operation of double lance injection when compared to the single one. This intensified the combustion efficiency of pulverized coal. For this reason, the pulverized coal injection system in the blast furnaces of CSC was modified from the conventional single lance to a double air-cooled coaxial lance system in 2000 [13].

Instead of cooling air, the coal combustion temperature could be promoted with oxygen flowing through the annulus of coaxial lance [14]. This oxy-coal injection technology has been adopted in many blast furnaces [15–18]. The PCI operation of CSC's blast furnaces might be improved if the cooling air for the coaxial lance is replaced by the enriched oxygen. However, the information regarding the application of oxygen enrichment in pulverized coal injection remains insufficient. To recognize the influences of lance configuration and oxygen enrichment pattern on the performance of PCI operation, a CFD based simulation model has been established in this study. Three different lance configurations, consisting of a single lance, a CSC's double lance, and an oxy-coal lance, are taken into account. The numerical predictions are able to provide a useful insight into the coal combustion behavior in the regions of blowpipe, tuyere, and raceway of a blast furnace. In addition, detailed discussion is made to reveal the impact of enriched oxygen on coal ignition and pressure loss across the combustion zone.

2. Methodology

The gas-particle flow and coal combustion in tuyere and raceway were calculated using FLUENT V12 code. The flow field and temperature distribution were described using 3-D, steady-state Reynolds-averaged Navier–Stokes equations in association with the RNG (Re-Normalization Group) k–ε turbulence model. The pulverized coal particles were treated as a dispersed phase using a Lagrangian method subject to the assumption that each particle followed a discrete trajectory without interactions with any of the other particles. The mathematical formulation is described below.

2.1. Gas-particle flow

2.1.1. Gas phase

Continuity:

$$\nabla \cdot (\rho U) = \sum \dot{m} \qquad (1)$$

where ρ is the density, U is the mean velocity, and $\dot{m}$ is the mass transfer rate from particulate to gas phase.Momentum: