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CFD simulation of two-phase gas-particle flow in the Midrex shaft furnace: The effect of twin gas injection system on the performance of the reactor

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ABSTRACT

In the present study a mathematical model is developed to examine the effect of dual gas injection system on the distribution of process variables and energy consumption in the Midrex shaft furnace. The developed model was constructed by considering the major chemical reactions and physical structures within the furnace and describes a counter-current moving bed reactor in which hematite pellets are reduced to sponge iron by pure hydrogen gas. Governing equations containing overall continuity, momentum, energy and mass equations are developed for both gas and solid phases in cylindrical coordinate system. Unreacted shrinking core model is implemented to simulate gas–solid reactions in the reactor. The complicated equations are solved by applying finite volume technique. The model is applied to simulate multiphase flow inside the reactor when it is equipped with one and two hydrogen gas intake ports to examine the impact of gas injection arrangement on the process variables. The radial and axial distributions of operational parameters including gas and solid temperature, fractional reduction of iron oxides and hydrogen and water vapor concentration are obtained for both cases. The results indicate that reduction degree and energy consumption are improved by utilizing dual gas injection system.

Introduction

A shaft furnace is a complex multiphase flow reactor containing gas and solid phases. Understanding the flow and heat transfer mechanism of these phases within the reactor can effectively help ironmaking industries to optimize iron reduction process in terms of energy consumption, greenhouse gas emission and productivity. Because of the surrounded process and the restrictions related to applying instrumentations, it is difficult to carry out experimental investigations. In addition sensitivity analysis of the effect of operational and geometrical variables on the performance of the reactor makes it extremely costly and time-consuming. As a result a mathematical modeling, as a cost-effective and capable technique, which precisely simulates the transport phenomena inside the reactor plays a significant role in the development of direct reduced iron technologies. Some of most well-known industrial processes producing direct reduced iron (or sponge iron) are Midrex, Armco, Purofer,

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Nomenclature

a_{gs}	special reaction surface, *1/m*
C_{ij}	concentration of species i in phase j, *mol/m³*
C_i^e	concentration of species i in equilibrium state, *mol/m³*
C_{tg}	total gas concentration, *mol/m³*
$C_{l,0}$,C_l	initial atomic oxygen concentration and atomic oxygen concentration of iron oxides in solid phase, respectively, g-atom O/m³
C_{pj}	heat capacity of phase j, *J/kg.K*
$D_{e,i}$, $D^*_{e,i}$	effective diffusivity of reactant and product species i, respectively in the pellet, *m²/s*
$D_{j,eff}$	effective diffusivity in j phase in the bed, *m²/s*
d_p	diameter of pellet, *m*
D_b	diameter of bed, *m*
f_l,f_h,f_m,f_w	local reduction of iron oxides, hematite–magnetite, magnetite–wustite, wustite–iron, respectively, –
F	overall reduction degree, –
G_0	mass velocity of gas, *kg/m².s*
h_{gs}	heat transfer coefficient between gas and particles, W/m².K
h_r	radiative heat transfer coefficient, W/m².K
$k_{r,il}$	reaction rate constant for species i at interface l, *m/s*
K	permeability of the bed, m
Ke_{il}	equilibrium constant of reaction with species i at interface l, –
$k_{m,i}$,$k^*_{m,i}$	mass transfer coefficient of species i at interface k, *m/s*
L	bed height, m
M	molecular weight, *g/mole*
$N_{j,d}$	diffusive molar flux in phase j, *mole/m².s*
Nu	Nusselt number, –
P	absolute pressure, *Pa*
Pe	Peclet number, –
Pr	Prandtl number, –
Q_0	volumetric flow rate of Hydrogen, *Nm³/h*
q_j	conductive heat flux in phase j, *w/m²*
R_0	pellet radius, *m*
R_b	bed radius, *m*
$\overline{R}$	universal gas constant, *kJ/kmolK*
R	rate of chemical reaction, *mol/m.s*
r	radial coordinate in cylindrical system, *m*
S_0	flow of solid, *ton/hr*
S_φ	source term in general discrete equation
Sc	Schmidt number, –
Sh	Sherwood number, –
T	temperature, *K*
$\vec{V}_j$	velocity vector, *m/s*
X_l	local fraction of unreduced iron oxides at each step of reduction, –
Y_i	mole fraction of gas, –
Z	axial coordinate in cylindrical system, m

Greek symbols

α_i	coefficient of each stage of reaction
ε_p	porosity of pellet, –
ε_b	porosity of bed, –
τ	tortuosity of pellet, –
$\lambda_{j,eff}$	effective thermal conductivity, W/m.K
μ_g	Gas viscosity, N.s/m²
ρ_b	density of bed, *kg/m³*
ρ_g	density of gas, *kg/m³*
ρ_p	density of pellet, *kg/m³*
σ	Stefan–Boltzmann coefficient, W/m²k⁴
ψ_j	Stream function, *kg/s*
ΔH	heat of reaction k, *j/mole*

Subscript

eff	effective parameter
g	refers to gas
H_2	related to hydrogen
in	related to inlet
l	related to interface of solid conversion
out	related to outlet
s	refers to solid

Corex and Hyl III [1–4]. In most of these processes iron oxide pellets are charged from top of the shaft furnace and move downward, while reducing gas is supplied laterally at the lower part of furnace and moves upward. Counter-current flow of reducing gas and iron oxide pellets produces sponge iron.

A review on the literature shows a large number of mathematical model are performed to estimate the distribution of variables within the reactor. However some assumptions and simplifications of real condition are seen in most of them. Some authors studied the transport phenomena in the shaft furnace one-dimensionally [5–19]. Their models were not capable to predict flow maldistribution which has significant effect on the performance of furnace [20,21]. Yagi and Szekely [22,23] carried out a mathematical modeling in moving bed reactor and investigated the effect of gas and solid maldistribution on the performance of the reactor. They neglected axial dispersion of heat and mass in the gas phase. They also assumed that the reducing gas is injected axially from the bottom of the reactor. However in industrial shaft furnaces reducing gas is radially introduced into the reactor, which has significant operational impact on iron reduction process. Valipour and Saboohi [24] presented a two-dimensional gas–solid flow in moving bed reactor and examined important operational variables inside the reactor such as gas and solid temperature, reducing gas mole fraction and reduction degree of iron oxide pellets. In recent years some researchers studied about Corex reduction process [25–27]. Wu et al. [25] developed a two-dimensional mathematical model to simulate Corex reduction process. They studied operational variables and reduction behavior inside the reactor. Numerical investigation of Corex shaft furnace by three-dimensional mathematical model was carried out by Xu et al. [27]. They obtained an optimal