The effects of kinetic parameters on combustion characteristics in a sintering bed

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ABSTRACT

Coke combustion is the main source of thermal energy for sintering of iron ores particles, and drastically affects the product sinter quality and productivity of the process. In this paper, simulation of coke combustion is performed for case studies comprising various operating parameters and coke sizes to assess the influence the coke combustion characteristics and operating conditions on sinter quality and productivity of the process. The sintering process was simulated with an unsteady-2D axisymmetric model. Effects of kinetic parameters including coke particles size, inlet air velocity, the amount of coke in the sintering charge and limestone particles size on product sinter quality and productivity of sintering process were studied. Simulation results of sintering process for coke sizes of 2 mm and 2.4 mm indicate that large particles size may reduce sinter quality and productivity. Combustion efficiency improves by optimization of the inlet air velocity. Moreover, simulation results for limestone particles size of 2 mm and 1 mm show that by decreasing the limestone particles size, the un-decomposed limestone in the bed may increase and sinter quality declines. Varying the amount of coke shows little change in the sintering time, but considerable change in the product sinter quality and energy consumption.

1. Introduction

The iron ore sintering process to produce improved blast-furnace charge is the main part of blast-furnace load preparation at modern iron making throughout the world. In the iron ore sintering process, a raw mix of iron ore, coke, limestone and moisture are charged on a moving grate and form a bed of 40—60 *cm* height. Hot gas jets from the ignition burners commence coke combustion at the top of the sintering bed, as shown in Fig. 1 [1].Beyond this point, the required air for the continuation of coke combustion in the bed is supplied via suction fans installed at the bottom of the bed. This causes the formation of a flame front at the top of the bed, which moves downward as the sintering bed travels. The flame front temperature is high enough to cause surface melting of the bed, which merges particles and forms the sinter product. The sinter grate speed is set such that the bed material is sintered by the time the grate reaches the discharge point.

With respect to the fuel costs, which account for the major share in the total costs, considerable saving in running costs may be obtained from relatively small increase in the efficiency of the sintering process. In an attempt to achieve this, numerical simulation is a substantial step to optimize the process regarding fuel consumption, product sinter quality and productivity.

In recent years many researchers have focused on the development of porous media combustion technology. This is mainly because combustion in porous media differs significantly from free flames due to two main factors: the high surface area of the porous media which provides an efficient heat transfer between the gas and the solids, and the well mixing of fuel and oxidant in porous media which augments effective diffusion and heat transfer in the gas phase. These phenomena may be referred to as internally self-organized process of heat recuperation [2]. Heat transfer mechanism in porous media results in several interesting characteristics such as higher burning speeds, extension of the lean flammability limits [3,4], and the low emission of pollutants [5,6]. Yoksenakul et al. [7] developed a SPMB (Self-Aspirating Porous Medium burner) for replacing the conventional gaseous fuel, free flame burners. They showed that SPMB yields a more complete combustion with relatively low CO and NO_x emission compared with conventional burning flames.

From energy storage point of view, Nagel and Shao [8, 9] studied thermo-chemical heat storage through a porous media. They

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Nomenclature

A (m^{-1})   specific surface of the bed
A_p (m^2)   external surface area
C_i (mol/m^3)   molar concentration of ith gaseous species
C_i^e (mol/m^3)   equilibrium molar concentration of ith gaseous
             species
C_{pg} (J/kg.K)   specific heat of gas
C_{ps} (J/kg.K)   specific heat of solid
$D_{eff,i}$ (m^2/s)   effective diffusivity coefficient of ith gaseous species
D_i (m^2/s) diffusion coefficient of ith gaseous species in the bulk
             gas
d_l (m)   diameter of limestone-calcium oxide interface
d_p (m)   initial diameter of limestone
D_p (m)   diameter of particle
D_t (m^2/s) thermal dissipation coefficient
f melting and solidification function
G fraction of original carbon
h (W/m^2.K) convective heat transfer coefficient
$K_{eff,i}$ (m/s) ash layer effective mass transfer coefficient of ith
             gaseous species
$K_{g,eff}$ (W/m.K) gas phase effective thermal conductivity
$K_{g,i}$ (m/s) bulk mass transfer coefficient of ith gaseous species
             through gas film
$K_{h,i}$ equilibrium constant of hematite reaction with ith
             gaseous species
K_l (Pa)   equilibrium constant of limestone decomposition
K_r (W/m.K) equivalent thermal conductivity for radiation
$K_{r,c,i}$ (m/s) chemical reaction rate constant of coke with ith
             gaseous species
$K_{r,h,i}$ (m/s) chemical reaction rate constant of hematite with ith
             gaseous species
$K_{r,l}$ (mol/m^2.s) chemical reaction rate constant of limestone
             decomposition
$K_{s,eff}$ (W/m.K) solid phase effective thermal conductivity
k_{wtr} (m/s) water mass transfer coefficient
n_c (m^{-3}) number of coke particles per unit volume
n_h (m^{-3}) number of hematite particles per unit volume
n_l (m^{-3}) number of limestone particles per unit volume
P (Pa)   static pressure

P_{H_2O} (Pa) vapor pressure
P_{sat} (Pa)   saturated vapor pressure
R (mol/m^3.s) reaction rate
R_i (mol/m^3.s) reaction rate of ith gaseous agent
R_u (J/mol.K)1 universal gas constant
R_{evp} (mol/m^3·s) evaporation rate
R_{Cond} (mol/m^3·s) condensation rate
r_R (mol/m^3·s) drying rate calculated from the partial pressure
             difference
r (m)   radius of hematite–magnetite interface
r_o (m)   initial radius of hematite
Sh Sherwood number
$SOURCE_g$ (J/m^3.s) source term of gas phase energy equation
$SOURCE_i$ (kg/m^3.s) source term of ith gaseous species
             transportation equation
$SOURCE_{mass}$ (kg/m^3.s) source term of continuity equation
$SOURCE_{momentum}$ (kg/m^2.s^2) source term of momentum
             equation
$SOURCE_s$ (J/m^3.s) source term of solid phase energy equation
T (K)   temperature
T_g (K)   gas temperature
T_m (K)   melting temperature
T_s (K)   solid temperature
t (s)   time
u (m/s)   air inlet mean velocity
V (m/s)   superficial velocity vector
w mass fraction of water in the bed
w_{cr} critical moisture content of the solids
w_r reduced moisture content of the solids
X_m logarithmic mean molar fraction of vapor
Y_i mass fraction of ith gaseous species

Greeks
$\Delta\theta_m$ (K) variations in melting temperature
λ shape factor
ε porosity
ξ particle area factor
ρ_g (kg/m^3) gas density
ρ_s (kg/m^3) solid density
μ (kg/m.s) gas dynamic viscosity

developed a versatile conceptual model based on thermodynamic principles and the theory of porous media. The validation and application of the model was investigated for a calcium hydroxide reaction system. Liu et al. [10] studied the cascade utilization of waste heat in sinter cooling bed with the aid of computational fluid dynamics. They examined the effects of different operating parameters on the cooling air temperature and waste heat utilization
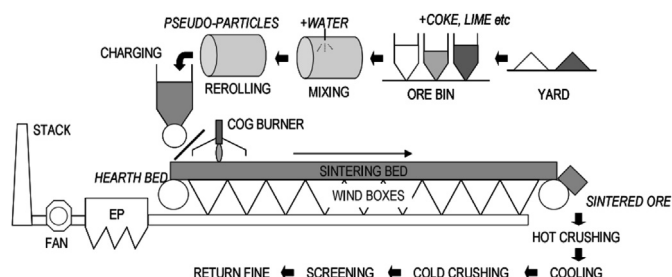

Fig. 1. Schematic of an iron ore sintering plant [1].

quantity. Their work includes a study of waste heat quality and quantity in terms of energy and exergy.

Fixed-bed processes are commercially used for the combustion and conversion of natural plant materials such as coal, wood, cellulose and tobacco for generation of power or production of gaseous or liquid products. A detailed mathematical model was developed by Miller et al. [11] to study the temporal and spatial solid–fluid reactions in spherically symmetric porous cellulose and wood particles. Chan et al. [12] presented a one-dimensional model of wood pyrolysis with inclusion of moisture release, tar cracking and char decomposition processes. Leach et al. [13] presented a one-dimensional transient model for forward smoldering, allowing local thermal and chemical non-equilibrium. Fatehi et al. [14] modeled the adiabatic reverse combustion in packed bed of wood particles, allowing local thermal and chemical non-equilibrium between the phases. This one-dimensional model was used to describe the propagation of the reaction front through the fuel bed. Hobbs [15] reviewed a broad treatment of the technology and modeling of coal fixed-bed systems.

Many researchers have modeled iron ore sintering process. The early model of Muchi and Higuchi [16] used the Ranz equation for