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Research Paper

Mathematical modeling of and parametric studies on flue gas recirculation iron ore sintering

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HIGHLIGHTS

- A comprehensive model to describe a flue gas recirculation sintering (FGRS) process.
- Determined kinetic parameters of raw materials via TGA to modify sub-models.
- FGRS can improve melt fraction and uneven heat distribution in sinter bed.
- FGRS deserves FFS attention, and input flue gas velocity exerts the greatest impact.

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ABSTRACT

A relatively more comprehensive 1D mathematical model, compared to previous models, is proposed for flue gas recirculation sintering (FGRS). The proposed model considers multiphase theory, eight major reactions significantly affected by the input gas conditions, and various heat transfer processes within/between different solid and gas phases. Characteristic size distributions of materials including coke, limestone and dolomite are used to correct the reaction rates of key sub-models, as well as specific kinetic parameters determined via thermogravimetric analysis instead of empirical values. Geometric changes caused by the reactive and melting factors are described in improved manners. This model is validated by contrasting the modeling results and the measured data from sinter pot tests. Parametric studies show FGRS technology can significantly enhance combustion characteristic within sinter bed, meaning to increase maximum temperature and melt fraction, improve the uneven distribution of heat. Therefore, the quality of sintered ore can be improved. However, the slightly reduced flame front speed deserves further attention. The velocity of input flue gas exerts the most significant effect, followed by O_2 concentration, and then, temperature. The operating parameters of FGRS must be carefully determined. Three measures, which still require further investigations, can be proposed to optimize the process.

1. Introduction

Flue gas recirculation sintering (FGRS) technology can reduce flue gas emissions and reuse waste heat effectively in iron ore sintering [1]. Five FGRS systems have been built or transformed in China since 2013. Fig. 1 shows a comparison between the typical FGRS and the conventional sintering (CS). Despite the significantly reduced environmental load and the slightly improved quality of sintered ore, issues in productivity and costs are becoming increasingly severe. According to Fan et al. [1,2], the flame front speed (*FFS*) of FGRS process reduced because of the increasing gas flow resistance and decreasing O_2 content in input flue gas under fixed suction applied. To maintain productivity, gas supply rate is generally increased, consequently the needed suction applied is enhanced, which in turn, the resultant power consumption, main fan loading, and costs of the subsequent waste gas treatment system will all be increased. In addition, the relatively rough production modes of Chinese enterprises always result in unnecessary waste. Therefore, further studies on FGRS technology are necessary.

Mathematical models have been performed to predict sintering behavior quantitatively [3–21]. Essential simplification processes have been found. Most of these models have been validated by data from sinter pot tests. Shibata [3] and Patisson et al. [4] mainly concentrated on predicting the moisture transfer process. Venkataramana et al. [5] focused on analyzing the effects of process

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Nomenclature

A	specific surface area, $m^2\ m^{-3}$; Pre-exponential factor, s^{-1}
B	parameters related to the surface structure of coke, –
C	molar concentration of gas phases, $mol\ m^{-3}$
C_p	specific heat, $J\ kg^{-1}\ K^{-1}$
d_p	equivalent diameter of the solid phases, m
$d_{p,ini}$	initial diameter of the solid phases, m
$d_{p,fin}$	final diameter of the solid phases, m
d_c	diameter of the un-reacted part of the solid phases, m
D	mass diffusion coefficient of gas phases, $m^2\ s^{-1}$
E	activation energy, $J\ mol^{-1}$
f_{ash}	ratio of mass of ash segregated and initial mass of ash (only coke, limestone, and dolomite are considered)
F	ratio of mass of solid phases and initial mass (only coke, limestone, and dolomite are considered)
h, h_{conv}	convection coefficient, $W\ m^{-2}\ K^{-1}$
H	height of sinter bed, m
I	radiation intensity, $W\ m^{-2}sr$
k_c	reaction rate constant, $m\ s^{-1}$
K_{eq}	reaction equilibrium constant, –
m_0	initial particle mass, $kg\ m^{-3}$; initial sample mass in TGA, mg
m_c	un-reacted part mass, $kg\ m^{-3}$; un-reacted sample mass in TGA, mg
m_∞	final sample mass in TGA, mg
M	molecular weight, $kg\ mol^{-1}$
n	particle number density, $1\ m^{-3}$
P	pressure, Pa
Po_s	internal pores ratio of ash layer (only coke, limestone, and dolomite are considered), –
Q	volumetric heat generation rate, $W\ m^{-3}$
R	reaction rate, $mol\ m^{-3}\ s^{-1}$
R_g	universal gas constant, $J\ mol^{-1}\ K^{-1}$
t	time, s
T	temperature, K
T_{in}	initial temperature of reaction commences in TGA, K
u	velocity, $m\ s^{-1}$
x	spatial coordinate along the direction of bed height, m
Y	mass fraction of solid and gas phases, –
ΔH	enthalpy of reaction, $kJ\ kg^{-1}$
ΔP	pressure drop across sinter bed, Pa
Nu, Pr, Re, Sh	particle Nusselt, Prandtl, Reynolds, and Sherwood number, respectively, –

Greeks

α	conversion of sample in TGA, –
β	mass transfer coefficient, $m\ s^{-1}$; heating rate in TGA, $K\ min^{-1}$
χ	polynomial correlation of the characteristic drying curve for raw materials, –
δ	ash layer thickness, m
ε	porosity of sinter bed or solid phases, –
ε_m	emissivity, –
φ	fraction of heat absorbed by solid, –
γ	volume fraction of solid and gas phases, –
κ	incomplete combustion coefficient, –
λ	conductivity, $W\ m^{-1}\ K^{-1}$
μ	gas dynamic viscosity, $kg\ m^{-1}\ s^{-1}$
ρ	density, $kg\ m^{-3}$
ς_j	solid phase shape factor, –
ξ	correction factor, –

Subscripts and superscripts

g	gas
s	solid
k	reaction index
i	gas species index ($i = N_2$, O_2, CO_2, CO, and H_2O)
j, jj	solid species index (j = sinter feed, returned fines, coke, limestone, dolomite, hydrated lime)
C	coke
L	limestone
H_2O	vapor or solid moisture
eff	effective diffusion
rad	radiation
ssa	specific surface area
$*$	saturation vapor; gas equilibrium concentration
ω	phase change factor dependent on factors

parameters like suction applied, ignition time and ignition gas temperature. Ramos et al. [6] incorporated the heat wave propagation through the sintering bed by combining the solutions of the various reaction rates and gas–solid heat transfer with the calculation of the granule movement by the discrete element method (DEM). It was Mitterlehner et al. [7] who proved the most sensitive parameters are the mean diameter, coke content and humidity of raw mix, bed porosity, and Fe_2O_3 content in sintered ore. Yang et al. [8,9] treated sinter solid materials as multiple solid phases and considered complicated modes of heat transfer including convection/radiation between gas and solid phases, conduction/radiation between solid phases, conduction/radiation within solid particles (in the same solid phases) and conduction in gas phase. On the basis of Yang's model [8,9], Kang et al. [14] discussed the effect of additional O_2 supply with an adjustment of injection location on the productivity and quality of sintered ore. Nath and Mitra [10,11] created a CFD-based model to obtain the optimum coke content in the two-layer sintering bed by applying a genetic algorithm optimization technique. Yamaoka and Kawaguchi [12] built a 3D model can calculate not only the progress of sintering reactions and the resultant structural changes but also the qualities of sintered ore. Komarov et al. [13] established a 2D model in which molten iron ores were regarded as non-fluid medium and intermediate gas species and ash in reaction sub-models were neglected. Zhou et al. [15] considered most of the important physicochemical reactions, in which coke, limestone, dolomite, and iron ore particles were treated with characteristic size distributions. Then, Zhao et al. [20] modified Zhou's model [15] by integrating into an available granulation model to provide a novel description of coke positioning within granules. Castro et al. [16,17] developed a 3D model which was also based on multiphase theory, similar to Yang's model [8,9], to predict the feasibility of partially replace the solid fuel by steelworks gases. Ahn et al. [18,19] made the first reported paper on the simulation study of FGRS process. They conducted a commercial flowsheet process simulator to build a 2D model to analyze the effects of various flue gas recirculation locations/ratios and flue gas injection locations in an industrial sinter strand on flue gas emissions. However, in this model, combustion zone expansion along the bed length and the pressure drop of gas flow through the bed were ignored. The model built by Pahlevaninezhad et al. [21] is probably the most recent model, in which the effects of kinetic parameters including coke content, coke particle size, limestone particle size and input air velocity, on combustion characteristic in a sinter bed were analyzed.