International Journal of Heat and Mass Transfer 97 (2016) 964–974

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Mathematical modeling and combustion characteristic evaluation of a flue gas recirculation iron ore sintering process

Gan Wang [a], Zhi Wen [a,b], Guofeng Lou [a,*], Ruifeng Dou [a], Xianwei Li [c], Xunliang Liu [a], Fuyong Su [a]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing 100083, China
[b] Beijing Key Laboratory of Energy Saving and Emission Reduction for Metallurgical Industry, University of Science and Technology Beijing, Beijing 100083, China
[c] Research Institute of Baoshan Iron and Steel Co., Ltd., Shanghai 201900, China

ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form 18 January 2016
Accepted 26 February 2016

Keywords:
Flue gas recirculation
Iron ore sintering
Mathematical modeling
Sinter pot test
Combustion characteristics

ABSTRACT

Flue gas recirculation sintering (FGRS) technology has been applied for two decades with the aim of reducing pollutant emissions. Compared with the conventional sintering (CS), the changes of input gas conditions may influence the bed combustion process greatly. Mathematical models have been developed to predict sintering behavior quantitatively, but few of the previous work focused on FGRS process. In this study, a multiphase theory-based mathematical model is established. This model considers nine kinds of major physicochemical reactions, in which six modes of gaseous reactions make it more comprehensive and accurate to model FGRS process. Heat transfer within/between different solid and gas phases are modeled in better manners. Geometric changes caused by reactive-factors are modeled in simple terms. Sub-models are available to simulate the effects of the temperature, gas supply, composition and content of recirculated gas on combustion characteristics in the sintering bed. Good agreements between simulated and measured results have been obtained from contrasting to six sinter pot tests based on FGRS technology. Four combustion parameters are selected to evaluate quantitatively the advantages and potential problems of FGRS technology. Results show that the flatter maximum temperature (*MaxT*) profile for FGRS compared with that for CS implies a stronger tumble strength of the sintered ore. The broader *MaxT* and combustion zone thickness (*CZT*) curve indicate a higher degree of melt fraction, together with a lower *FFS* and productivity. To better investigation, further parameter simulation and process optimization of FGRS technology is necessary.

1. Introduction

Reducing pollutant emissions and increasing energy efficiency motivate the research in new process in iron and steel industry, especially for iron ore sintering, which produces 20% pollutant of iron and steel industry. Several types of flue gas recirculation sintering (FGRS) technology were developed in last two decades for these purposes. Fig. 1 shows a typical schematic of FGRS process. FGRS process is advantageous compared with conventional sintering (CS) procedure because the former can substitute part of either flue gas from the sinter strand or hot air from the cooler for ambient air as the input gas, which can distinctly reduce environmental load. Thus, FGRS has been applied in industrial production in China since its introduction in 2013, and five sets of systems have been built or transformed. The main input gas conditions for FGRS technology such as velocity, temperature, composition and contents, may differ across methods because the sources of recirculated gas vary. A series of effects in heat and mass transfer, physicochemical reactions, and bed structural change are then generated during the sintering process. Therefore, further investigation is necessary, particularly on optimizing the operating parameters of the FGRS process.

A lot of researches have been carried out on the sintering process, via experiments [1–3] and mathematical models [4–22], in the last 15 years. Mathematical models have been developed to predict quantitatively the sintering performance. Most of these models are 1D transient (along the direction of bed height) [4–16], in which the transfer phenomena along the directions of grate length and width are neglected. Fig. 2 shows that the 1D and 2D representations are undoubtedly [9], indicates that 1D model is enough to represent the sintering process mathematically.

More than half of current models have strived to describe the complicated phenomena of combustion and heat and mass transfer in a sintering bed without considering geometric changes in the

---

* Corresponding author. Tel.: +86 10 62332730; fax: +86 10 62329145.
E-mail address: lgf@ustb.edu.cn (G. Lou).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.02.087
0017-9310/

Nomenclature

A	specific surface area, $m^2 \cdot m^{-3}$; pre-exponential factor, s^{-1}
B	parameters related to the surface structure of coke, –
C	molar concentration of gas phases, $mol \cdot m^{-3}$
C_p	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
d_p	solid phase mean diameter, m
d_{pore}	average hydraulic diameter of internal pores in ash layer, m
D	mass diffusion coefficient of gas phases, $m^2 \cdot s^{-1}$
D_k	Knudsen diffusion coefficient, $m^2 \cdot s^{-1}$
E	activation energy, $J \cdot mol^{-1}$
FFS	flame Front Speed, $cm \cdot min^{-1}$
h, h_{conv}	convection coefficient, $W \cdot m^{-2} \cdot K^{-1}$
H	height of the sintering bed, m
I	radiation intensity, $W \cdot m^{-2} sr$
k_c	reaction rate constant, $m \cdot s^{-1}$
K_{eq}	reaction equilibrium constant, –
m_0	mass density of the initial particle, $kg \cdot m^{-3}$
m_c	mass density of the un-reacted part, $kg \cdot m^{-3}$
M	molecular weight, $kg \cdot mol^{-1}$
$MaxT$	maximum temperature of the sintering bed, K
n	particle number density, $1 \cdot m^{-3}$
P	pressure, Pa
Q	volumetric heat generation rate, $W \cdot m^{-3}$
r_0	radius of the initial particle, m
r_c	radius of the un-reacted part, m
R	reaction rate, $mol \cdot m^{-3} \cdot s^{-1}$
R_g	universal gas constant, $J \cdot mol^{-1} \cdot K^{-1}$
t	time, s
T	temperature, K
u	velocity, $m \cdot s^{-1}$
W_{cr}	critical solid moisture content,%
x	spatial coordinate along the direction of bed height, m
Y	mass fraction of solid and gas phases, –
ΔH	heat of reaction, $J \cdot kg^{-1}$
ΔP	pressure drop across the sintering bed, Pa
Nu	particle Nusselt number, –
Pr	particle Prandtl number, –
Re	particle Reynolds number, –
Sc	particle Smit number, –
Sh	particle Sherwood number, –

Greeks

β	mass transfer coefficient, $m \cdot s^{-1}$
χ	polynomial correlation of the characteristic drying curve for iron ore particles, –
δ	ash layer thickness, m
ε	porosity of sintering bed or solid phases, –
ε_m	emissivity, –
φ	fraction of heat absorbed by solid, –
γ	volume fraction of solid and gas phases, –
κ	stoichiometric coefficient, –
λ	conductivity, $W \cdot m^{-1} \cdot K^{-1}$
μ	gas dynamic viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
ρ	density, $kg \cdot m^{-3}$
τ	tortuosity in solid phase, –
σ	Stefan–Boltzmann constant, $W \cdot m^{-2} \cdot K^{-4}$
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, H_2, CH_4, and H_2O)
j, jj	solid species index (j = sinter feed, return fine, 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

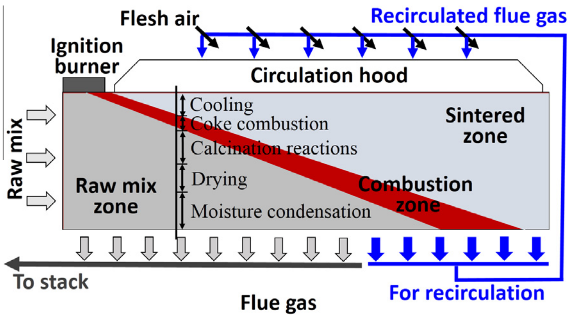

Fig. 1. Schematic of the FGRS process in an iron ore sintering bed.

bed [4–11,17–19]. Among these, Shibata [4] and Patisson et al. [5] mainly concentrated on predicting the moisture transfer process, whereas the remaining primarily predicting the bed temperature distribution and combustion characteristics. Venkataramana et al. [6] created a model to see the effects of process parameters like suction applied, ignition time and ignition gas temperature, while Pahlevaninezhad et al. [11] focused on kinetic parameters including coke contents, coke particles size, limestone particles size and input air velocity. Nath and Mitra [8] created a CFD-based model to obtain the optimum coke contents in the two-layer sintering bed by applying a genetic algorithm optimization technique. Zhou et al. [9] built a mathematical model to consider most of the important physicochemical reactions, in which coke, limestone, dolomite, and iron ore particles were treated with characteristic size distributions. Thereafter, Zhao et al. [10] made an improvement on Zhou et al.'s research by integrating into an available granulation model to provide a novel description of coke positioning within granules. This modified model resulted in greater agreements with experimental results than Zhou et al.'s and is probably the most recent model. Komarov et al. [17] established a 2D model

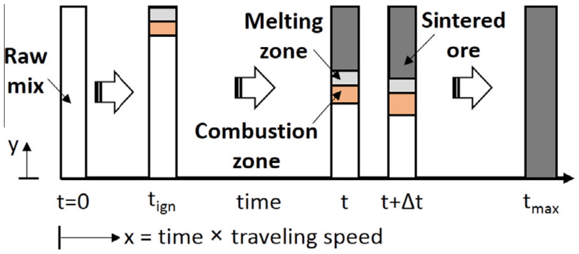

Fig. 2. Extension of 1D transient model to 2D steady model.