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Predictive models and operation guidance system for iron ore pellet induration in traveling grate–rotary kiln process

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ABSTRACT

Thermal state of iron ore pellets in industrial traveling grate–rotary kiln process cannot be revealed straightforward, which is unfavorable for field operations. In this study, coupled predictive models of pellet thermal state within traveling grate and rotary kiln were established. Based on the calculated temperature profiles, predictive model of pellet compression strength was also established to assist in process optimization. All the models proposed were validated by the industrial data collected from a domestic plant, and the results show that grate model possesses a high accuracy, kiln model is considered to be accurate to within 10–15% of actual values, and strength model can identify the variation of pellet strength caused by the thermal changes. The proposed models were embodied into an operation guidance system developed for a large-scale pelletizing plant, and the system running results illustrate that the predictive models and expertise rules established can optimize the process very well.

1. Introduction

In the past few decades, iron-making industry in China has soared up due to the rapid development of economy. According to China Steel Association, the domestic production of pig iron exceeded 700 Mt in 2013. Besides the production, burdens of blast furnace have improved from sinter ores of low basicity incorporated with lump ores to sinter ores of high basicity incorporated with acid iron ore pellets. These two main factors lead to an increase of pellet production in China. Fig. 1 shows the iron ore pellet production at home and abroad together with domestic pig iron production in the past 10 years. Processes of producing iron ore pellets mainly include vertical shaft furnace, moving grate and traveling grate–rotary kiln. Although the investment and operating cost of shaft furnace is low, this process is confronted with market shrink due to its low productivity and the requirement of magnetite. Moving grate process requires special alloys that are comparatively expensive and rarely produced in China, thus its application is restricted. Traveling grate–rotary kiln process has the advantages such as large handle capacity, multiple fuel capacity and good adaptability to various materials, and it has become a major process of producing iron ore pellets in the domestic recently.

A main task of operating grate–kiln system is to stabilize the thermal state and to guarantee a good pellet consolidation. Undoubtedly, accurate measurements of gas/solid temperature within these two devices are fundamental to a better control of this process. Even though many types of equipments have been installed to efficiently monitor the process variables in most pelletizing plants, thermal state of pellet bed remains opaque. Another criterion concerning is pellet strength, at present, mechanical strength of iron ore pellets cannot be measured until they are discharged from the cooler (there exists about half a production cycle between pellet roasting and strength measurement). This hysteretic feedback of product quality may be adverse to the operations especially at highly fluctuating thermal state. In such cases, predictive models on pellet thermal state and pellet strength need to be constructed to assist in optimizing the grate–kiln operations.

In the present work, adopting the mass and heat balance equations and certain kinetic expressions of corresponding phenomena, predictive models on thermal state within grate–kiln process were established. The coupling of grate model and kiln model, which has been less discussed previously, was particularly realized to visualize the entire thermal process. Prediction of pellet strength based on time–temperature profile was conducted as well. Finally, an industrial instance of the established models was given, in which an operation guidance system containing predictive models and expertise rules was developed to optimize the production of a domestic pelletizing plant.

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Nomenclature

A	gas–pellet apparent contact area, m^{-1}
A_i	area per unit kiln length, m
AF	stoichiometric air–fuel ratio, mass basis
b_1	thickness of refractory bricks, m
b_2	thickness of steel shell, m
C_g	specific heat of gas, J/(kg K)
C_p	specific heat of pellet, J/(kg K)
C_{O_2}	concentration of oxygen, kg/m^3
$C_{O_2}^e$	equilibrium concentration of oxygen, kg/m^3
d_p	pellet diameter, m
d_i	diameter of rotary kiln, m
D_e	hydraulic diameter of the kiln, m
$D_{H_2O}^e$	effective diffusivity of water, m^2/s
D_{O_2}	diffusivity of oxygen, m^2/s
Er_i	radiactive heat transfer coefficient
F_L	flame length, m
G	superficial gas flow rate, $kg/(m^2\ s)$
G_F	momentum flow rate of fuel, $kg\ m/s^2$
G_{pa}	momentum flow rate of primary air, $kg\ m/s^2$
h_{eff}	heat transfer coefficient within grate, $J/(m^2\ s\ K)$
h_i	heat transfer coefficient within kiln, $J/(m^2\ s\ K)$
H	bed depth in rotary kiln, m
k_g	thermal conductivity of gas, J/(m s K)
k_p	thermal conductivity of pellet, J/(m s K)
k_m	first order rate of magnetite oxidation, m/s
k_{O_2}	mass transfer coefficient of oxygen, m/s
k_w	mass transfer coefficient of water vapor in the gas, m/s
m_F	mass flow rate of fuel, kg/s
m_g	mass flow rate of gas, kg/s
m_s	mass flow rate of solid, kg/s
m_{pa}	mass flow rate of primary air, kg/s
MVF	materials volumetric flow rate, m^3/s
n	rotational speed of kiln, r/s
Nu	Nusselt number
P	gas pressure, Pa
Pr	Prandtl number
r_m	radius of unreacted magnetite core, m
r_p	radius of pellet, m
r_w	radius of wet core of the pellet, m
R	radius of rotary kiln, m
R_{fuel}	rate of fuel combustion, kg/s
R_m	rate of magnetite oxidation, $kg/(m^3\ s)$
$R_w(R_{cd})$	rate of water evaporation/condensation, $kg/(m^3\ s)$
Re_D	axial Reynold's number
Re_p	pellet Reynold's number
Re_w	angular Reynold's number
t	time, s
T_i	temperature, K
u	moving velocity of pellet in the kiln, m/s
w_P	pellet moisture content, mass%
W_g	moisture content of the gas, kg/m^3
W_g^e	equilibrium concentration of water vapor between gas and pellet, kg/m^3
y	bed height in traveling grate, m
z	position along kiln axis, m

Greek symbols

α	kiln inclination angle, rad
ε_b	voidage of pellet bed
ε_i	emissivity
ρ_{air}	density of air, kg/m^3
ρ_b	bulk density of pellet bed, kg/m^3
ρ_{cp}	density of combustion product, kg/m^3
ρ_e	equivalent density of gas, kg/m^3
ρ_F	equivalent density fuel, kg/m^3
ρ_g	gas density, kg/m^3
ρ_m	density of magnetite, kg/m^3
μ_g	gas viscosity, Pa s
v_g	gas velocity, m/s
λ_1	thermal conductivity of refractory bricks, W/(m K)
λ_2	thermal conductivity of steel shell, W/(m K)
ΔH_w	enthalpy of evaporation/condensation, kJ/kg
ΔH_m	enthalpy of magnetite oxidation, kJ/kg
ϕ	pellet sphericity, taken to be 0.9
φ	filling angle, rad
θ_d	dynamic repose angle, rad
η	filling degree of pellet in the kiln
χ	empirical constant, taken to be 0.15
Φ_i	heat flux per unit kiln length, W/m

Subscripts

g, p, w, s, a	gas, pellet, wall, solid, ambient
wi, wo, wu, wc	inner, outer, uncovered, covered wall
rgw, rgs, rws, rwa	gas/wall, gas/solid, wall/solid, wall/atmosphere radiation
cgw, cgs, cws, cwa	gas/wall, gas/solid, wall/solid, wall/atmosphere convection

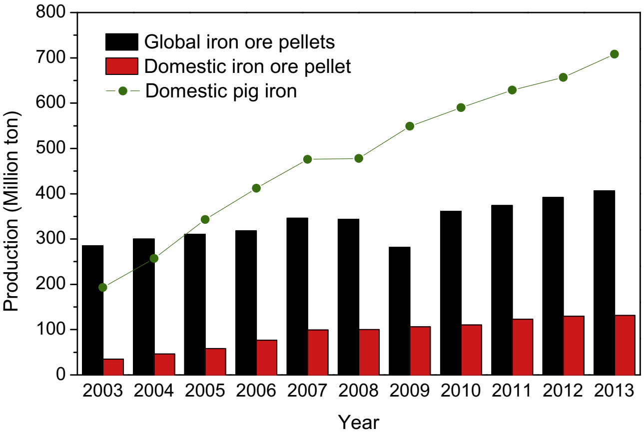

Fig. 1. Pig iron and iron ore pellet production in past ten years.

2. Previous investigations

As understood, grate–kiln process is a combination of horizontally moving grate and circumferentially rotating kiln. Mathematical simulations on pellet thermal state within moving grate can be seen in many literatures (Barati, 2008; Majumder et al., 2009; Sadrnezhaad et al., 2008; Thurlby et al., 1979), since moving grate process accounts for two thirds of the world's installed pelletizing processes capacity. The mathematical models are mass and heat balance equations incorporated with kinetic expressions of physical and chemical phenomena, which includes evaporation and condensation of pellet moisture, oxidation of magnetite, combustion of coke breeze, calcination of lime or dolomite, pellet shrinkage, etc. Rotary kilns are ubiquitous fixtures of the metallurgical and chemical process industries, the mathematical models of rotary kiln generally involve solid motion (Boateng and Barr,