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Optimization of Cooling Process of Iron Ore Pellets Based on Mathematical Model and Data Mining

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Abstract: Cooling process of iron ore pellets in a circular cooler has great impacts on the pellet quality and systematic energy exploitation. However, multi-variables and non-visualization of this gray system is unfavorable to efficient production. Thus, the cooling process of iron ore pellets was optimized using mathematical model and data mining techniques. A mathematical model was established and validated by steady-state production data, and the results show that the calculated values coincide very well with the measured values. Based on the proposed model, effects of important process parameters on gas-pellet temperature profiles within the circular cooler were analyzed to better understand the entire cooling process. Two data mining techniques—Association Rules Induction and Clustering were also applied on the steady-state production data to obtain expertise operating rules and optimized targets. Finally, an optimized control strategy for the circular cooler was proposed and an operation guidance system was developed. The system could realize the visualization of thermal process at steady state and provide operation guidance to optimize the circular cooler.

Key words: iron ore pellet; circular cooler; model; data mining; optimization

Symbol List

A——Gas/pellet apparent contact area, m^2/m^3;
C_g——Heat capacity of gas, kJ/(kg·K);
C_p——Heat capacity of pellet, kJ/(kg·K);
C_{O_2}——Oxygen concentration in gas phase, kg/m^3;
$C_{O_2}^e$——Equilibrium oxygen concentration needed for reaction, kg/m^3;
d_p——Pellet diameter, m;
D_{O_2}——Diffusivity of oxygen within pellet, m^2/s;
G——Superficial gas flow rate, $kg/(m^2·s)$;
h_{eff}——Effective heat transfer coefficient, $J/(m^2·s·K)$;
k_g——Thermal conductivity of gas, J/(m·s·K);
k'_m——First order oxidation rate of magnetite, m/s;
k_{O_2}——Mass transfer coefficient in oxygen gas, m/s;
Nu——Nusselt number;
Pr——Prandtl number;
r_m——Radius of unreacted magnetite core, m;
r_p——Radius of single pellet, m;
Re_p——Reynold′s number of pellet;
R_m——Rate of oxidation of magnetite, $kg/(m^3·s)$;
t——Moving time of pellets, s;
T_g——Gas temperature, K;
T_p——Pellet temperature, K;
z——Bed height, m;
σ——Standard deviation;
λ——Fraction of heat from oxidation;
ΔH_m——Enthalpy of oxidation, kJ/kg;
ρ_b——Bulk density of pellet bed, kg/m^3;
ρ_m——Density of magnetite, kg/m^3;
ε_b——Void fraction of pellet bed.

Due to the development of ironmaking industry and the improvement of blast furnace (BF) burdens, the production of iron ore pellets in China has been increasing substantially since 1990s. Shaft furnace, moving grate and traveling grate-rotary kiln are three main processes of producing oxidized iron ore pellets. Possessing the advantages such as large handling capacity and good adaptability to various materials, traveling grate-rotary kiln has become a major process of producing iron ore pellets in China recently. In this process, circular cooler is generally selected as the cooling equipment due to its small footprint and efficient heat exploitation. The optimization of traveling grate and rotary kiln has been reported previously[1-3], and this paper mainly concerns the cooling process.

Mathematical model is able to reveal the gas-solid temperature profiles at steady state and elucidate how process parameters influence the cooling process. Gas-

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solid heat exchange in the cooler has been studied previously[4-6] and the behaviors of corresponding physical-chemical phenomena tend to be simulated on FLUENT recently[7-10]. These simulations are subjected to design and off-line optimization rather than on-line operation guidance. When these models are applied online, the characteristics of industrial data and requirements of model inputs need to be well considered. Besides model, optimization of cooling process can be efficiently accomplished by expertise rules obtained by analyzing historical production data[11]. However, the optimization of circular cooler using data mining techniques has been seldom reported.

The objective of this work is to optimize cooling process using mathematical model and data mining techniques. The optimization here refers to the visualization of cooling process the determination of set values of process parameters at steady state, and the stabilization of the system via expertise rules at fluctuating state. A steady-state mathematical model of pellet cooling was established in this study, and then Association Rules Induction and Clustering were applied on steady-state data to further obtain the optimized rules and targets. Finally, an operation guidance system was developed for a pelletizing plant.

1 Model Visualization

1.1 Process description

A schematic view of typical grate-kiln-cooler process for iron ore pellets is shown in Fig. 1. Traveling grate (for drying and preheating) is divided into sections of up-draught drying (UDD), down-draught drying (DDD), primary pre-heating (PH1) and secondary preheating (PH2), and circular cooler is divided into three sections (Zone 1, Zone 2 and Zone 3) to attain hot gas of different temperatures. To optimize energy consumption, off-gas from Zone 1 is re-circulated to rotary kiln as secondary air, and off-gas from Zone 2 is re-circulated to PH1 through PH1 exhauster while off-gas from Zone 3 is re-circulated to UDD.

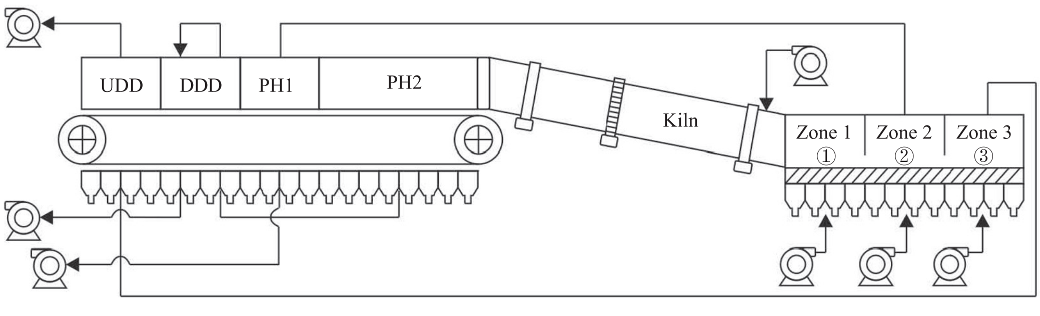

Fig. 1 Schematic view of typical grate-kiln-cooler process

The manipulated variables of cooling process are pellet bed height, cooling air flowrate and moving speed of cooler, which are chosen to control the cooling rate. Low cooling rate may result in low off-gas temperature, which is a downside for traveling grate. High cooling rate may result in high temperature of discharged pellets, which damages the traveling belts in subsequent transportation. Cooling process has the characteristics of large inertia, nonlinearity and strong coupling, and the internal thermal state of circular cooler can be hardly measured. Therefore, model visualization is of great significance for appropriate operations of pellet cooling.

1.2 Heat and mass transfer model

As shown in Fig. 1, cooling air blowing from three fans in cooling process goes through air ducts, grate plates, pellet bed and vessel hoods sequentially while pellet bed moves along with trolleys circumferentially. The cooling process of a Chinese pelletizing plant was studied, and the process parameters are listed in Table 1.

To establish a mathematical model of cooling process, several assumptions have to be made: (1) Effective cooling zone is regarded as a cuboid where height is bed height and base area is cooling area; (2) Cooling air goes through pellet bed evenly from bottom to top and conducts cross-flow heat exchange with bed, neglecting the air leakage and channeling; (3) Temperature gradient along the width of grate plate and temperature gradient

Table 1 Process parameters of a Chinese pelletizing plant with throughput of 600 t/h

Item	Value	Unit
Specification	ϕ21.94×3.65	m×m
Cooling area	230.6	m^2
Moving speed of cooler	1.71−2.05	m/min
Bed height	752−772	mm
Hood temperature of Zone 1	900−1 250	°C
Hood temperature of Zone 2	700−1 180	°C
Hood temperature of Zone 3	260−380	°C
Pressure drop of Zone 1	About 2 500	Pa
Pressure drop of Zone 2	About 2 500	Pa
Pressure drop of Zone 3	About 2 500	Pa