MATHEMATICAL MODEL AND COMPUTER SIMULATION OF MOISTURE TRANSFER PROCESS DURING SINTERING①

Zou, Zhiyi Huang, Tianzheng Yang, Xiaosheng Chen, Ji
Department of Mineral Engineering,
Central South University of Technology, Changsha 410083

ABSTRACT An improved mathematical model for the whole range moisture transfer process of iron ore sintering, based on the fundament of simultaneous heat and mass transfer in the moist zone, has been developed. On the basis of this model, the moisture transfer process during sintering was simulated numerically using computer. The model can serve as a predictive tool and operating guide for controlling the termperature in bed, determining suitable moisture level of raw mix and decreasing the harmful influence of overmoistened zone.

Key words: mathematical model computer simulation sintering moisture transfer

1 INTRODUCTION

Moisture transfer is an important step in the sintering operation because of the high thermal energy consumption required for drying(up to 25 per cent of the total requirement for iron ore sintering) and the reduction in permeability of the overmoisture zone, which obstructs gas flow. This process has great influence on the yield and the quality of the sinter. However, few papers were specifically concerned with the study of moisture transfer during sintering. Its study is not far from perfect. Therefore, in view of theory and practice, it is still very significant to further clarify the law of moisture transfer process.

This paper has developed an improved mathematical model for the whole moisture transfer process of iron ore sintering, on the basis of the analysis of the moisture transfer process, mass balance and energy conversion. This process is simulated on computer using the mathematical model.

2 MATHEMATICAL MODEL

2.1 *Mechanism of Model*

In moist zone, there occurs the moisture transfer-drying and the condensation. Modelling is based on the heat and mass transfer in the moist zone. The drying of the material bed is divided into two periods of constant drying rate and decreasing drying rate. Supposing that the latter rate linearly falls with the decreasing of the moisture content in the bed, the water condensation in the moist bed is assumed to proceed when a temperature between the solid and the gas temperatures, and the partial pressure of water vapour exceeds the saturation vapour pressure of water at an arbitrarily chosen temperature between the solid and bulk gas temperatures.

2.2 *Assumptions*

The main assumptions are as follows:

(1) Gas flow is"piston flow";

(2) Gas species are ideal;

(3) The system is adiabatic;

(4) The different state variables are functions of bed height Z and time θ;

(5) The heat and mass transfer is only by convection;

(6) The water transfer includes two stages of drying and condensation;

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(7) ε, a_g, h_p, and d_e are assumed to be constant;

(8) C_{ps}, C_{pg} are considered as functions of temperature and components in the moist zone;

(9) It can be assumed that the accumulation terms of gas elements are zero;

(10) The inside temperature of a solid particle is identical to its surface temperature. The temperature gradient can be neglected.

2.3 *Fundamental Equation*

In terms of a differential volume element of cross-section with a thickness ∂Z, shown in Fig. 1, the equilibrium calculation of heat, mass and momentum is carried out, and the fundamental equations describing the water transfer can be attained as follows (see nomenclature for symbols):

Thermal balance of the gases:

$$u\rho_g C_{pg}\frac{\partial T_g}{\partial Z} = a_g h(T_s - T_g) \tag{1}$$

Thermal balance of the solids:

$$u\rho_g C_{pg}\frac{\partial T_s}{\partial \theta} = a_g h(T_g - T_s) - M_{H_2O}\gamma_{H_2O}L_v(T_s) \tag{2}$$

Water vapour balance of the bulk gas:

$$u\frac{\partial C_{H_2O}}{\partial Z} = \gamma_{H_2O} \tag{3}$$

Moisture balance of the solids:

$$\frac{\partial W_{H_2O}}{\partial \theta} = -M_{H_2O}\gamma_{H_2O} \tag{4}$$

Mass balance of the gas:

$$\frac{\partial \rho_g}{\partial Z} = M_{H_2O}\gamma_{H_2O} \tag{5}$$

Mass balance of the solids:

$$\frac{\partial \rho_a}{\partial \theta} = -M_{H_2O}\gamma_{H_2O} \tag{6}$$

Momentum balance (using Ergun's relationship):

$$\frac{\Delta P}{L} = A \cdot \mu \cdot u + B\rho_g u^2 \tag{7}$$

$$A = 150\frac{(1-\varepsilon)^2}{de^2 \cdot \varepsilon^3} \tag{7a}$$

$$B = 1.75\frac{1-\varepsilon}{de \cdot \varepsilon^3} \tag{7b}$$

In the present case, the initial boundary conditions are as follows:

$$\theta = 0,\ Z \geqslant 0:\ T_s = T_{s,0},\ W_{H_2O} = W_{H_2O,0},\ \rho_a = \rho_{a,0}$$

$$Z = 0,\ \theta \geqslant 0:\ T_g = T_{g,0},\ C_{H_2O} = C_{H_2O,0},\ \rho_g = \rho_{g,0} \tag{8}$$

2.4 *Kinetic Equations for Moisture Transfer*

The important parameter in the above balance equations is the rate of moisture transfer, γ_{H_2O} ($mol \cdot s^{-1} \cdot m_{bed}^{-3}$). Researchers used different equations to calculate it. In this study, on the basis of the simultaneous transmision fundament of heat, mass and momentum transfer and film theory, a new general γ_{H_2O} model has been put forward which is universal for the whole range simulation and can be solved quickly. Its deducing process of the kinetic equation is omitted here[1].

Model of the moisture transfer rate γ_{H_2O} is:

$$\gamma_{H_2O} = \begin{cases} \gamma_R & \gamma_R < 0 \\ \gamma_R & \gamma_R \geqslant 0 \text{ and } W \geqslant W_{cr} \\ \dfrac{W}{W_{cr}} \cdot \gamma_R & \gamma_R \geqslant 0 \text{ and } W < W_{cr} \end{cases} \tag{9}$$

The moisture transfer rate in the boundary gas layer at the surface of the particles, γ_R is:

$$\gamma_R = a_g K\frac{(P_{V_{sat}} - P_{H_2O})}{RT_g} \tag{10}$$

The coefficient of mass transfer K is:

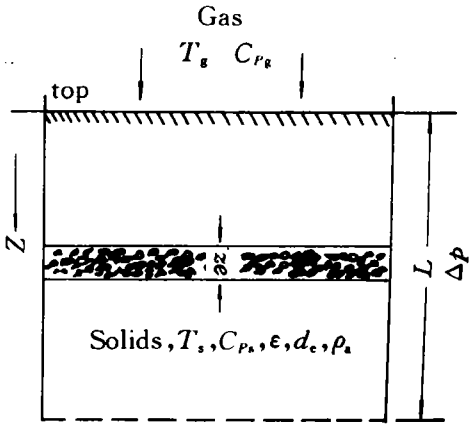

Fig. 1 Different volume element of the moist zone

$$K = \frac{1}{\rho_g C_{pg}} \tag{11}$$

2.5 *Determination of the Parameters in the Model*

2.5.1 Determination of the values of ε, d_e, by the least square method

It is very difficult to measure directly the parameters of bed structure, and to ensure the accuracry of the obtained datum. The parameter estimation theory provides us an effective method.

The value of voidage and equivalent diameter of particles are calculated from Ergun's equation with the least square method by measuring the change of the gas flow rate u with that of pressure drop ΔP.

The parameters estimation was carried out with Siemens-7570-C in Fortran programme. The calculation results of structure parameters were: $\varepsilon = 0.4$, $d_e = 2.5$ mm.

2.5.2 Calculation of the heat capacity of gas and solid phases and the coefficient of heat transfer h_P

(1) The determination to the heat capacity of gas and solid phases

In general, the heat capacity of mixture is calculated by:

$$C_P = \sum_{i=1}^{n} X^i C_P^i \tag{12}$$

According to the composition of gas and solid phases, their heat capacity can be gained as:

$$C_{Pg} = 8.81 \times 10^2 + 0.62 T_g - 2.37 \times 10^{-4} T_g^2 \tag{13}$$

$$C_{Ps} = 7.53 \times 10^2 + 0.26 T_s \tag{14}$$

(2) Calculation of the heat transfer coefficient h_P

The heat transfer coefficients calculated by Ranz-Marshall formula are:

$$N_u = 2.0 + 0.6 (R_e/\varepsilon)^{1/2} P_r^{1/3} \tag{15}$$

$$h_P = N_u \cdot \lambda_s / d_e \tag{16}$$

$$P_r = C_P \cdot \mu / \lambda_g$$

$$R_e = d_e / \mu$$

$$\lambda_g = 0.0244 (T_g/273.15)^{0.82} \tag{17}$$

$$\mu = 1.720 \times 10^{-5} \times (T_g/273)^{1.5} \times 386.1(113 + T_g) \tag{18}$$

3 SIMULATION OF MOISTURE TRANSFER PROCESS

3.1 *Numerical Solution Technique*

The first-order quasi-linear hyperbolic characteristics of the model provide the convinience for the system centralization treatment—conversion of partial differential equations set into the ordinary one. The model is centralizingly treated along the characteristic curve by the characteristic curve method [2]. Two ordinary differential sets gained consist of a stiff problem, which is difficult to be solved by using general numerical methods. In this study, a modified version of the three-order semi-implicit Runge-Kutta method developed by Michelson[3] is used to integrate the two ordinary differential equation sets. For the simulations presented here, $\Delta\theta = 20$ s and $\Delta Z = 6$ mm.

It proved that the calculation speed is 10 times faster than that of the four-order Runge-Kutta method in solving the model by actual operation on computer.

Fig. 2 is the complete flowsheet of calculation.

3.2 *Simulation results and Discussion*

On the base of the mathematical model, the simulation to moisture transfer during sintering process was carried out. Simulation calculation was done in Siemens-7570-C computer installed in CSUT. In the case of 500 mm bed height and 20 min for whole process, the computation time is about 60 s. After imputting the information of the characteristics of raw mixture, the properties of inlet gas flow and the operating conditions, the compater can estimate the temperature field in sintering bed, and dynamic response to all variables related to moisture transfer process. The simulation results are shown in Fig. 3 ~ Fig. 7.

3.2.1 Simulation on predrying experiment

Simulated predrying experiment is proceeded with total suction in beds keeping constant at 8820 Pa, draughting hot gas(400 ℃)

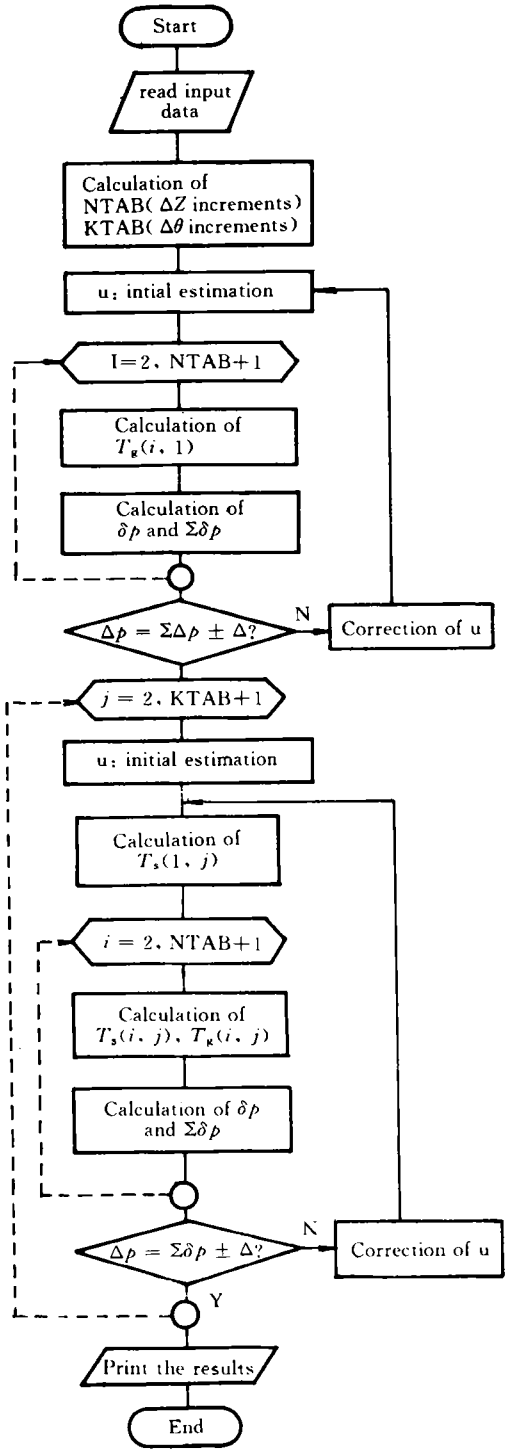

Fig. 2 Flow diagram of simulation calculation

down through the beds. It was simulated on the computer respectively using ordinary materials and pre-heating materials. The simulation results are shown in Fig. 3~Fig. 4.

From Fig. 4, preheating can increase the heatfront speed of the beds.

3. 2. 2 Simulation on influence of various factors on moisture transfer

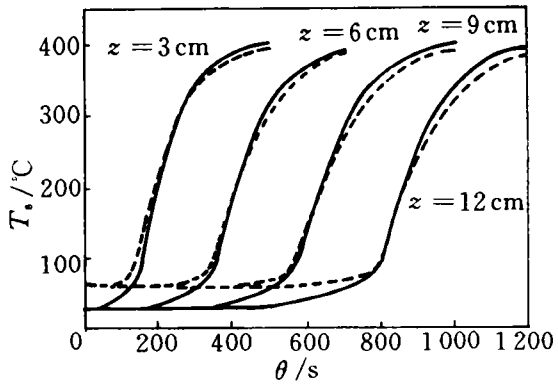

Fig. 3 Simulation on solid temperature vs time during predrying experiment(iron ore)

full line—standard; dot line—preheating(60 ℃)

calculation conditions:

$\varepsilon = 0.4$, $d_c = 2.5\times10^{-3}$ m,

$W_{cr} = 0.05$, $h_p = 248\ W\cdot m^{-2}\cdot k^{-1}$, $T_{g,0} = 673$ K,

$C_{H_2O,0} = 16.8\ mol\cdot m^{-3}$, $\rho_{g,0} = 1.293\ kg\cdot m^{-3}$,

$T_{s,0} = 300$ K, $W_{H_2O,0} = 1.452\times10^{2}\ kg\cdot m_{bed}^{-3}$,

$\rho_{a,0} = 1.96\times10^{3}\ kg\cdot m^{-3}$, $P = 8.82\times10^{3}$ Pa

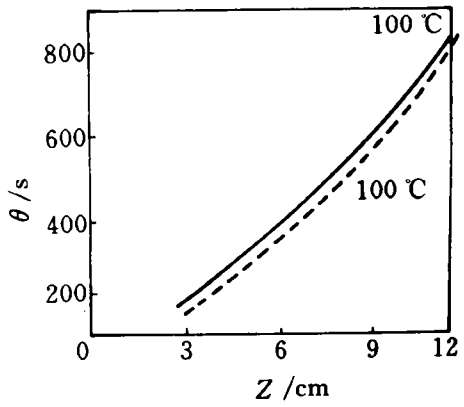

Fig. 4 The influence of the preheating on the heatfront speed of bed

full ine—standard; dot line—preheating

conditions are the same as that in Fig. 3

It is known that the characteristic of the sintering materials and the operating condition greatly affect the moisture transfer during sintering process. Following is the simulation study on the effects that the bed structure coefficient and the initial material temperature impose on the moisture transfer process.

Fig. 5 shows the changes of the bed temperature curves, with the equivalent diameters of particles, while the other conditions are stable.

From this figure, when the equivalent diameter of particles increases, the bed permeability increases, and the heat transfer condition between the gas and the solid phases in the bed is improved, which makes the bed temperature rise faster. It can be further deduced that increase of equivalent diameter of particles may shorten the sintering time and increase the yield.

Fig. 6 shows the changes of the moisture content of the mixture along the height of bed respectively in the beds of ordinary materials and of preheated materials (60 ℃). It can be seen from it that:

(1) Overmoistened phenomena is not serious. The maximum water content in the moist zone of bed is not more than 9%, that is to say that the water content of the bed can be increased by 1% at most.

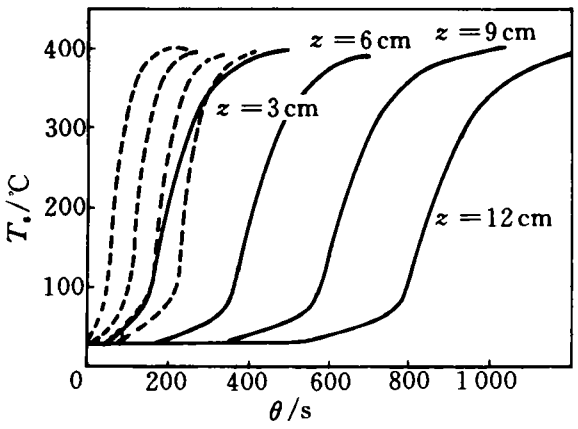

Fig. 5 Influence of equivalent diameter(d) of particles on the solid temperature vs time

dot line— d =5 mm; full line— d =2.5 mm; calculation condition is the same as that in Fig. 3

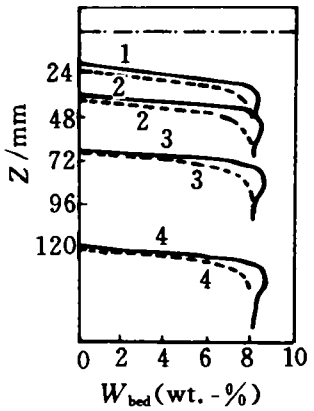

Fig. 6 Changes of water content of mixture along the height of bed.

full ine—standard; dot line···pre-heating(60 ℃); 1—100 s; 2—200 s; 3—400 s; 4—800 s; calculation condition is the same as that in Fig. 3

(2) When the initial temperature of the beds is higher than 60 ℃, overmoistened phenomenon at the lower level of the beds can be eliminated completely(theoretically).

(3) The average water content of the beds of preheating materials is fewer than that of the ordinary materials, so the wet bulb of the former is also lower than that of the latter. That is to say that the difference between the wet bulb temperature and the initial temperature of the beds is smaller for the former than that for the latter, so the amount of condensed moisture is reduced obviously, and the overmoistened phenomena is decreased or eliminated.

3.3 *Comparison of computed and measured results in sinter-pot*

In order to examine the validity of the mathematical model, pre-drying tests with the mixed iron ore powder of Longyan Iron and Steel Plant in Fujian as raw materials were carried out by using a laboratory-scale sintering-pot (d150 mm × 500 mm). The temperature distribution in beds was measured, and the simulation calculation was proceeded under the defined conditions. Fig. 7 shows the comparison of the measurement and the calculation changes of bed-temperature with time

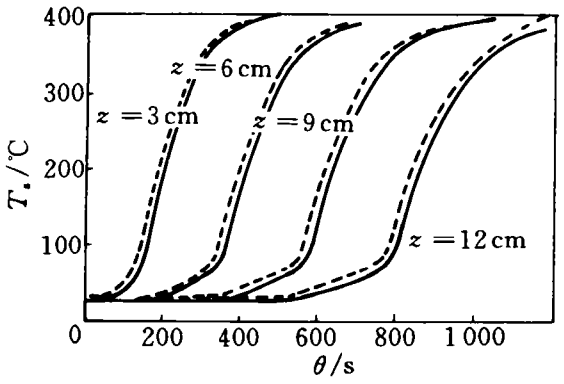

Fig. 7 Comparision of measured and computed solid temeprature vs time during pre-drying experiment

full line—computed; dot line - - - ···measured

during pre-drying experiment, and the computation results are agreeable well with the measured ones.

4 CONCLUSION

A new whole-range mathematical model of moisture transfer process is developed, which is easy to be solved quickly. Based on it, the dynamic simulations on this process have been proceeded. The simulation results are satisfactory. The model can be used to calculate dynamic response to all variables related to moisture transfer process. It serves as a predictive tool and operation guide for controlling the temperature in bed, determining suitable moisture level of raw mixture and decreasing the harmful influence of overmoistened zone.

NOMENCLATURE

a_g Specific area of the bed ($m^2 \cdot m_{bed}^{-3}$)

C_{H_2O} Molar water vapor concentration in gases ($mol \cdot m^{-3}$)

C_{Pg}, C_{Ps} Heat capacity of the gases and the solids, respectively ($J \cdot kg^{-1} \cdot K^{-1}$)

d_e Equivalent diamenter of particles (m)

h_P Heat transfer coefficient ($m \cdot s^{-1}$)

L Height of the bem (m)

L_v Heat of vaporzation of water ($J \cdot kg^{-1}$)

M_{H_2O} Molecular weight of water ($kg \cdot mol^{-1}$)

N_u Nusselt number (-)

P_r Prandtle number (-)

P_{H_2O} Partial vapor pressure of water (Pa)

$P_{V_{sat}}$ Saturation vapor pressure of water (Pa)

γ_{H_2O} The rate of moisture transfer ($mol \cdot s^{-1} \cdot m_{bed}^{-3}$)

R Constant of ideal gas law ($J \cdot mol^{-1} \cdot K^{-1}$)

R_e Reyolds number (-)

T_g, T_s Temperature of the gases and the solids (K)

u Superficial velocity of the gas ($m \cdot s^{-1}$)

W Moisture content of the solids (kg/kg dry)

W_{cr} Critical moisture content of the solids (-)

W_{H_2O} Moisture content of the solids per unit volume of the bed ($kg \cdot m_{bed}^{-3}$)

X^i Molecular fraction of component i (-)

Z, ΔZ Distance into bed, distance interval, respectively (m)

θ, $\Delta\theta$ Time elapsed and time interval (s)

ε Porosity of the bed (-)

ρ_a Apparent density of the bed ($kg \cdot m_{bed}^{-3}$)

ρ_g Density of the gas ($kg \cdot s^{-1} \cdot m^{-1}$)

λ_g Thermal conductivity of gas ($W \cdot m^{-1} \cdot s^{-1}$)

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