A Differential Analysis for the Cost Minimum Operation of Iron Ore Sintering Machines

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In order to analyze and explore the cost minimum operation in iron ore sintering, a differential equation of cost change with respect to various operational factors was derived from a constitutive formula of energy cost for a unit sinter production; and then the equation was modified to a few equations describing the cost-minimum state and determinants guiding directions for four different operational actions.

As an example for the former equations, the operation under the minimum consumption ensures the relation between yield (η) and coke content (%C) like $\delta\eta/\delta(\%C) = \eta/\%C$.

The operation-guide determinants were derived for coke, bed height, bulk density and burnt lime action; then, the factors affecting the sign of each determinant were discussed. In any action case the ratio of partial costs was a critical factor to decide the direction of action. Moreover in case of bed height and burnt lime actions, the coefficient of yield with respect to bed height ($\beta\eta_H$) and that of bed permeation with respect to burnt lime content ($\beta\kappa_{BL}$) were critical, respectively.

KEY WORDS: agglomeration; bed height; bulk density; burnt lime content; coke content; cost minimum operation; differential analysis; iron ore sintering.

1. Introduction

Process modeling generally aims at process design and control, which has been developing with knowledge of chemical engineering and aids of computer capable of numerical integration of differential equations for heat and mass transfer.

In the iron ore sintering, Muchi *et al.*¹⁾ developed a computing method for heat wave in 1967; the method prevailed over Japan in 1970's for estimating the effect of operational factors. In 1982 Sato *et al.* started to model the other unit processes from granulation²⁾ to melting,³⁾ pore⁴⁾ and mineral formation,⁵⁾ sinter strength estimation,⁶⁾ and finalized in 1987 their works with a total model⁷⁾ that predict sinter qualities from the initial ore blends. Recently Kano *et al.* applied DEM to visualize particle movement during granulation⁸⁾ and charging,⁹⁾ and pore formation¹⁰⁾ in the sinter cake during sintering.

In optimizing operation of a process, especially working and indicating the current values of relevant valuables, it is not necessary to specify the values of objective valuables like the integration of differential equation; but it is enough to get the sign of derivatives of the objective valuables with respect to operational valuables, which suggests which direction the operator change the valuables to. Few is the information, but sufficient for operators because they know the step of single actions by accumulated empirical knowledge, which is usually extracted by regression analysis on the past operational data, and they have another chance of re-adjusting with the on-line monitoring results. Though such approach must be popular in practical operation, the knowledge is closed probably because it belongs to a key know-how and remains in

an unsophisticated form to publish.

Segawa¹¹⁾ used a differential approach to discuss heat balance and production cost for blast furnace and melting furnace; whereas, none seems to have shown about sintering machine. The purpose of this paper is to develop a differential equation that describes sintering cost from basic relationships between relevant operational variables/parameters and to discuss the cost-minimum state and the direction for cost-minimum operation by applying the equation.

2. Differential Equations

We start with reviewing definitions of unit consumptions relevant to sintering operation. The objective variable is the energy cost of unit sinter production (Cost) as follows:

$$\text{Cost} = @_C \cdot \text{CR} + @_G \cdot \text{GR} + @_E \cdot \text{ER} \dots \dots \dots (1)$$

Unit consumptions for coke (CR), COG (GR) and electricity (ER) in Eq. (1) and air consumption (VR) are also defined by relevant parameters as follows:

$$\text{CR} = 10 \cdot \%C/\eta \dots \dots \dots (2)$$

$$\text{GR} = C_0/P_{Sr} \dots \dots \dots (3)$$

$$\text{VR} = V/P_{Sr} \dots \dots \dots (4)$$

$$\text{ER} = a \cdot P_V \cdot \text{VR} \dots \dots \dots (5)$$

, where %C: coke content (mass%, raw mixture basis)
C₀: COG flow rate (Nm³/h)
H: bed height (m)

ρ_m :	bed bulk density	(t/m ³)
η :	yield (=sinter/raw mixture)	(-)
P_{Sr} :	sinter production rate	(t/h)
V :	airflow rate	(Nm ³ /h)
P_V :	suction pressure	(kPa)
a :	constant	(Kwh/Pa/Nm ³)

Then, the sinter production rate (P_{Sr}) in Eq. (4) should be explained by parameters concerning sintering operation. A constitutive formula for production rate of sintering machine is:

$$P_{Sr} = \rho_m \cdot H \cdot W \cdot PS \cdot \eta \dots \dots \dots (6)$$

, where W : pallet width (m)
 PS : pallet speed (m/h)

Moreover, we need a couple of well known empirical relationships. One is for flame front speed (FFS), which is assumed to be proportional to airflow rate (V); the other is for bed permeability:¹²⁾

$$FFS = b \cdot (\rho_g \cdot c_g / (\rho_m \cdot c_m)) \cdot (V / (W \cdot L)) \dots \dots \dots (7)$$

$$V / (W \cdot L) = \kappa \cdot (P_V / H)^n \dots \dots \dots (8)$$

, where c_m, c_g : heat capacity of raw mixture and gas(J/t)

ρ_g :	air density	(t/m ³)
b :	constant	(m ²)
L :	strand length	(m)
κ :	bed permeability constant	((Nm ³ /h/m ²)/(kPa/m) ⁿ)
n :	bed permeation constant	~0.6 (-)

FFS can be replaced with the strand-ward point where the flame front attains to the bottom of bed (BTP) using the geometric relationship between them:

$$BTP = PS \cdot (H / FFS) / L \\ = (\rho_m \cdot c_m / (\rho_g \cdot c_g)) \cdot PS \cdot H \cdot W / (b \cdot V) \dots \dots \dots (9)$$

The above equations from Eqs. (1) to (9) are readily to convert into differential forms from Eqs. (1') to (9') as follows, respectively, with the symbol ' δ ' denoting total differential.

$$\delta(\text{Cost}) = @_C \cdot \delta(CR) + @_G \cdot \delta(GR) + @_E \cdot \delta(ER) \dots \dots \dots (1')$$

$$\delta(CR)/CR = \delta(\%C)/\%C - \delta\eta/\eta \dots \dots \dots (2')$$

$$\delta(GR)/GR = \delta C_0/C_0 - \delta P_{Sr}/P_{Sr} \dots \dots \dots (3')$$

$$\delta(VR)/VR = \delta V/V - \delta P_{Sr}/P_{Sr} \dots \dots \dots (4')$$

$$\delta(ER)/ER = \delta P_V/P_V + \delta(VR)/VR \dots \dots \dots (5')$$

$$\delta P_{Sr}/P_{Sr} = \delta \rho_m/\rho_m + \delta H/H + \delta(PS)/PS + \delta\eta/\eta \dots \dots \dots (6')$$

$$\delta V/V = \delta \kappa/\kappa + n \cdot \delta P_V/P_V - n \cdot \delta H/H \dots \dots \dots (8')$$

$$\delta(BTP)/BTP = \delta \rho_m/\rho_m + \delta H/H + \delta(PS)/PS - \delta V/V \dots \dots \dots (9')$$

, where W, L, a, b, c_m, ρ_g , and c_g have disappeared because they are constants. Moreover, Eqs. (6') and (9') makes

$$\delta P_{Sr}/P_{Sr} = \delta(BTP)/BTP + \delta V/V + \delta\eta/\eta \dots \dots \dots (10)$$

The above equations will transform to the goal equation (15) for a sintering machine under a steady state operation as follows:

The steady state operation ensures $\delta P_{Sr} = \delta(BTP) = 0$,

which simplifies Eq. (3') to Eq. (11), Eq. (4') to Eq. (12) and Eq. (10) to Eq. (13).

$$\delta(GR)/GR = \delta C_0/C_0 \dots \dots \dots (11)$$

$$\delta(VR)/VR = \delta V/V \dots \dots \dots (12)$$

$$\delta V/V + \delta\eta/\eta = 0 \dots \dots \dots (13)$$

Substituting $\delta V/V$ for $\delta P_V/P_V$ by Eq. (8') and using Eqs. (12) and (13), Eq. (5') becomes

$$\begin{aligned} \delta(ER)/ER &= \delta P_V/P_V + \delta V/V \\ &= (1 + (1/n)) \cdot \delta V/V - (1/n) \cdot \delta \kappa/\kappa + \delta H/H \\ &= - (1 + (1/n)) \cdot \delta\eta/\eta - (1/n) \cdot \delta \kappa/\kappa + \delta H/H \dots \dots \dots (14) \end{aligned}$$

Substituting Eqs. (2'), (11) and (14) into Eq. (1'), the change of energy cost finally becomes:

$$\begin{aligned} \delta(\text{Cost}) &= -C_C \cdot (\delta\eta/\eta - \delta(\%C)/\%C) + C_G \cdot (\delta C_0/C_0) \\ &\quad - C_E \cdot ((1 + (1/n)) \cdot \delta\eta/\eta + (1/n) \cdot \delta \kappa/\kappa - \delta H/H) \dots \dots \dots (15) \end{aligned}$$

In case of machines driven with a dumper-controlled main blower, δP_V can be zero, which simplifies the last equation as follows:

$$\begin{aligned} \delta(\text{Cost}) &= -C_C \cdot (\delta\eta/\eta - \delta(\%C)/\%C) + C_G \cdot (\delta C_0/C_0) \\ &\quad - C_E \cdot \delta\eta/\eta \dots \dots \dots (16) \end{aligned}$$

, where partial costs of $@_C \cdot CR$, $@_G \cdot GR$ and $@_E \cdot ER$ are replaced to C_C , C_G and C_E , respectively.

Specifying operational conditions more in detail and introducing empirical coefficients between parameters will modify Eqs. (15), (16) to more useful equations that link various actions to the change of energy cost. The section three will feature the cost minimum state with equations derived by letting the left side of Eqs. (2), (3) and (15) equal zero; the section four will relate to how to climb to the cost minimum state with determinants for various actions that indicates the sign of $\delta(\text{Cost})$ in Eq. (15), namely the direction of action to take.

3. Well-Developed Operation Around Cost Minimum State

3.1. Change of Yield with Coke Action and Change of Cost with Yield

Suppose an operator adjusts coke content (%C) only. At lower %C the up action can increase the yield enough to compensate coke consumption (CR) increase by the addition, resulting in CR cutting; whereas, at higher %C the sufficient increase in yield cannot follow the action, resulting in CR increase. Such consideration implies the existence of CR minimum point with respect to %C.

Around the CR minimum operation $\delta(CR)$ becomes zero in Eq. (2'), which gives the coefficient of yield with respect to coke content like

$$\delta\eta/\delta(\%C) |_{(\text{at CR} = \text{min})} = \eta/\%C \dots \dots \dots (17)$$

Similar consideration for C_0 , after substituting Eq. (19) into Eq. (3') and neglecting $\delta(BTP)$ and δV , gives the coefficient of yield with respect to COG gas flow rate for ignition like

$$\delta\eta/\delta C_0 \text{ (at GR = min)} = \eta/C_0 \dots\dots\dots (18)$$

These equations, (17) and (18), estimate the effects of coke and gas on yield around CR and GR minimum points, respectively.

Suppose an engineer intends to modify his sintering machine and needs to estimate the benefit in cost under a constant sinter production. Letting only $\delta\eta$ terms remain in Eq. (15) gives the following derivative of cost with respect to yield for his sintering machine:

$$\delta(\text{Cost}) = -(C_C + (1 + (1/n) \cdot C_E)) \cdot \delta\eta/\eta \dots\dots\dots (19)$$

He can calculate the cost cutting by assigning the yield gain to the $\delta\eta$ term in Eq. (19) that the modification will create.

3.2. Relations in Cost Minimum State

The cost minimum state expectedly attains in well-developed operation after bed height maintained usually at full level and material blend is kept constant, namely $\delta(\text{Cost}) = \delta H = \delta \kappa = 0$. Then, Eq. (15) becomes

$$(C_C + (1 + (1/n) \cdot C_E)) \cdot \delta\eta/\eta = C_C \cdot \delta(\%C)/(\%C) + C_G \cdot \delta C_0/C_0 \dots\dots\dots (20)$$

As coke cost takes large part of the energy cost, the coke cost likely exists around its own minimum state and Eq. (17) is valid. Then, substituting $\delta(\%C)/(\%C)$ for $\delta\eta/\eta$,

$$\delta C_0/\delta(\%C) = (C_0/(\%C)) \cdot (1 + (1/n) \cdot C_E)/C_G \dots\dots\dots (21)$$

Equation (21) describes the replacement ratio of coke and COG under the cost minimum state.

4. Cost Minimum Direction

The cost-minimum point of operation may be moving with changing circumstance. It sometimes occurs due to drift of unknown factors that integrated process models take no account of. In practical operation, however, just suggestion of what kind of action and in which direction to choose will be enough for operators to seek for it by try-and-error method.

There are several case studies below available for taking actions of coke content, bulk density, bed height and quick lime content. A determinant - an indicator of direction to action for the cost minimum operation - will appear for each case and the sign of the determinant will be examined in terms of relevant parameters/conditions.

4.1. Coke Action

From Eq. (15), let us introduce a determinant for coke action and illustrate it with a figure.

When we take coke action, we can let all of δH , δC_0 and $\delta \kappa$ equal zero. Defining the coefficient of yield with respect to coke content as $\beta\eta_{\%C} = (\delta\eta/\eta)/(\delta(\%C)/\%C)$ and substituting $\beta\eta_{\%C} \cdot (\delta(\%C)/\%C)$ for $\delta\eta/\eta$, Eq. (15) becomes

$$\delta(\text{Cost}) = D_{\%C} \cdot (\delta(\%C)/\%C) \dots\dots\dots (22)$$

$$D_{\%C} = -\beta\eta_{\%C} (C_C + C_E \cdot (1 + (1/n)) + C_C$$

$D_{\%C}$ in Eq. (22) is the determinant of coke action. Note that $\delta(\text{Cost})$ is free of C_G . If $D_{\%C}$ is negative, operator should increase coke content (Up action); if positive, he should decrease it (Down action) for the cost minimum operation point.

Figure 1 illustrates the behavior of the determinant with the coefficient ($\beta\eta_{\%C}$) on x-axis and the cost ratio of coke on electricity (C_C/C_E) on y-axis, which includes a line on which $D_{\%C}=0$ in case of $n=0.6$. $D_{\%C}$ is negative in the region under the line; $D_{\%C}$ is positive over it.

The current values of partial costs: C_C and C_E are known at any moment; the value of the coefficient ($\beta\eta_{\%C}$) has been standardized by the analysis of past operational data for the sintering machine. Operators, therefore, can readily calculate the sign of the determinant and find out the direction for cost minimum point, up or down of coke action.

4.2. Bed Height Action

Secondly we will focus on actions of bed height. Similarly to the case of coke action in 4.1, putting $\delta(\%C) = \delta C_0 = 0$; assuming $\delta\rho_m = \delta\kappa = 0$; defining the coefficient of yield with respect to bed height as $\beta\eta_H = (\delta\eta/\eta)/(\delta H/H)$, Eq. (15) becomes:

$$\delta(\text{Cost}) = D_H \cdot (\delta H/H) \dots\dots\dots (23)$$

$$D_H = -\beta\eta_H \cdot (C_C + (1 + (1/n)) \cdot C_E) + C_E$$

D_H is the determinant of bed height action. Negative D_H guides to up action; positive D_H suggests down action.

Figure 2 includes a line on which $D_H=0$ in case of $n=0.6$, showing critical effect of $\beta\eta_H$ on the sign of D_H :

- when $\beta\eta_H > n/(n+1)$ (~ 0.38), always $D_H < 0$;
- when $0.38 < \beta\eta_H < 0.05$, the sign of $\beta\eta_H$ depends on C_C/C_E ;
- when $\beta\eta_H < 0.05$, almost $D_H > 0$.

The coefficient ($\beta\eta_H$) is a machine characteristic and used to increase with the grate area as it was 0.1 for Sakai (177 m²); 0.3 for Tobata (320 m²); 0.5 for Oita (500 m²). This seemed to come from the fact that bigger machines had longer

Fig. 1. A schematic diagram of determinant for coke action, visualizing Eq. (22) in case of parameter $n=0.6$.

Fig. 2. A schematic diagram of determinant for bed height action, visualizing Eq. (23) in case of parameter $n=0.6$.

strand length resulting in higher feeding rate (t/h/m) that decreased vertical segregation of coke in bed;¹³⁾ an ‘avalanche phenomenon’ caused the decrease according to Inazumi *et al.*¹⁴⁾ Since recent modification of charging equipment to intensify the segregation must have decreased the $\beta\eta_{-H}$, the traditional thinking of operation that ‘higher bed height, better operation’ may turn to false for such machines.¹⁵⁾

4.3. Bulk Density Action

Thirdly, this section concerns bulk density. Assuming that yield is independent on bulk density, which is valid for $\rho_m < 2.0$ according to Inazumi *et al.*,¹³⁾ restricting the case taken without bed height change and defining the coefficient of permeability with respect to bulk density as $\beta\kappa_{\rho_m} = (\delta\kappa/\kappa)/(\delta\rho_m/\rho_m)$, Eq. (15) becomes:

$$\begin{aligned} \delta(\text{Cost}) &= D\rho_m \cdot (\delta\rho_m/\rho_m) \dots\dots\dots (24) \\ D\rho_m &= -\beta\kappa_{\rho_m} \cdot (1/n) \cdot C_E \end{aligned}$$

$D\rho_m$ is the determinant of bulk density action. Negative $D\rho_m$ suggests up action; positive $D\rho_m$, down action.

Since $\beta\kappa_{\rho_m}$ is negative, $D\rho_m$ is always positive obviously. Therefore, Eq. (24) suggests that decreasing bulk density is the never-changing direction for the cost reduction.

Typical machines are controlling bulk density by adjusting difference in the heights of float rollers and a cut gate; therefore, it is preferable for the difference to be minimized as far as surface of bed maintains its smoothness. It is also reasonable for many¹⁶⁻¹⁸⁾ to attempt modifications about charging equipment to reduce bulk density.

4.4. Burnt Lime Action

The last case is for burnt lime (BL), which acts as a binder to increase productivity.¹⁹⁾ The problem in this section is how to optimize the use under a constant productivity operation. The mechanisms for BL to increase productivity is so complicated²⁰⁾ that we consider only permeation effect for simplicity with the definition of the BL’s coefficient on permeability as $\beta\kappa_{BL} = (\delta\kappa/\kappa)/(\delta(\%BL)/\%BL)$.

Let a partial cost term of BL ($C_{BL} = @_{BL} \cdot BLR$) join in Eq. (1) to modify Eq. (15). For optimizing operation, there are two options: [Case I] the excess permeability that BL raises shall compensate for blower electricity; [Case II] the increase in bed height shall consume it for yield increase. Therefore, we need to introduce determinants for both cases and compare them to choose the better case. Defining the determinants as the same form as before, that is:

$$\delta(\text{Cost}) = D_{BL} \cdot (\delta(\%BL)/\%BL) \dots\dots\dots (25)$$

For Case I ($D_{BL(I)}$), the D_{BL} becomes

$$D_{BL(I)} = -(\beta\kappa_{BL}/n) \cdot C_E + C_{BL};$$

for Case II ($D_{BL(II)}$), the D_{BL} becomes:

$$D_{BL(II)} = -(\beta\kappa_{BL} \cdot \beta\eta_{-H}/n) \cdot (C_C + (1 + (1/n)) \cdot C_E) + (1 - \beta\kappa_{BL} \cdot \beta\eta_{-H}/n) \cdot C_{BL}.$$

Operators should choose Case I if $|D_{BL(I)}| > |D_{BL(II)}|$ otherwise Case II; then he should action ‘cut’ if the larger determinant is positive or ‘add’ if negative. **Figure 3**, depicting the determinants on the axis of dimensionless partial cost of BL and coke normalized by that of electricity, will facilitate such decision. Each case corresponds to the eight regions

		Choice of case	
		Case I	Case II
$D_{BL(I)}$	$D_{BL(II)}$	$ D_{BL(I)} > D_{BL(II)} $	$ D_{BL(I)} < D_{BL(II)} $
+	+	(3) BL: Down	(2) BL: Down
+	-	(4) BL: Down	(5) BL: Up
-	+	(8) BL: Up	(1) BL: Down
-	-	(7) BL: Up	(6) BL: Up

Fig. 3. A schematic diagram for choosing the case of burnt lime action, visualizing Eq. (25). $\beta_I = \beta\kappa_{BL}/n$, $\beta_{II} = \beta\kappa_{BL}\beta\eta_{-H}/n$.

separated by four lines for $D_{BL(I)} = 0$, $D_{BL(II)} = 0$, $D_{BL(I)} - D_{BL(II)} = 0$, and $D_{BL(I)} + D_{BL(II)} = 0$.

From up/down action’s point of view, the regions of (1) to (4) indicate ‘down’ action; those of (5) to (8) are for ‘up’ action. The critical line appears when $D_{BL(I)} + D_{BL(II)} = 0$; the equation is transformed to

$$\begin{aligned} (1 + (1/n) + C_C/C_E) - ((2n/(\beta\kappa_{BL} \cdot \beta\eta_{-H})) - 1) \\ \cdot C_{BL}/C_E + 1/\beta\eta_{-H} = 0 \dots\dots\dots (26) \end{aligned}$$

Figure 4 gives the visual understanding for Eq. (26). Obviously, up/down action depends on the magnitudes of the coefficients, $\beta\kappa_{BL}$ and $\beta\eta_{-H}$.

The condition of $D_{BL(I)} = D_{BL(II)} = 0$ is a requisite for the cost minimum operation in terms of BL action. The point locates at the intersection of the lines, shown as A in Fig. 3, leading to a relationship between partial costs at the cost minimum operation like:

$$\begin{aligned} C_{BL} : C_C : C_E &= (\beta\kappa_{BL}/n) \cdot (1 - \beta\kappa_{BL} \cdot \beta\eta_{-H}/n) : \\ &(\beta\kappa_{BL} \cdot \beta\eta_{-H}/n) \cdot (1 + (1/n) + \beta\kappa_{BL}/n) : \\ &1 - \beta\kappa_{BL} \cdot \beta\eta_{-H}/n \dots\dots\dots (27) \end{aligned}$$

4.5. Application of the Determinants

Partial cost ratios are critical to decide the direction of action, which are changing with economical circumstance. For example, electric power charge usually has day-night difference, which causes the significant oscillation in the partial cost ratios; gas unit price depends on its surplus/deficit situation at the steel works. The method using various determinants will help for quick actions against such change in circumstance.

In case of bed height and BL action, the coefficients of $\beta\eta_{-H}$ and $\beta\kappa_{BL}$ are also critical. The $\beta\eta_{-H}$ depends on machines; the $\beta\kappa_{BL}$ varies with the dosage of BL at the moment. Taking sleepless care of the coefficients will improve the accuracy of actions.

Fig. 4. A schematic diagram of determinant for burnt lime action, visualizing Eq. (26). (a) $n=0.6$, $\beta\kappa_{BL}=0.1$; (b) $n=0.6$, $\beta\eta_{H-H}=0.3$.

As discussed above, the differential analysis, if simple, has provided us a powerful tool to understand the cost-minimum state and to pursue the cost-minimum operation with determinants. Some operators must already have their computer guide cost-relating jobs with spreadsheet software. That is a practice of the differential analysis. This paper has also provided a comprehensive and theoretical basis for such jobs.

5. Concluding Remarks

From definitions of unit consumptions and several well-known empirical relationships for sintering operation, a differential equation for the change in energy cost (Eq. (15) or (16)) is introduced and then the equation is modified to various relationships that describe cost-minimum states and determinants to guide operational actions.

Equations (17) and (18) are examples of the former relationships. Equation (17) gives the coefficient of yield with respect to coke content at the minimum coke consumption; Eq. (18) gives the coefficient of yield with respect to ignition intensity at the minimum gas consumption. Equation (15) has potential to lead to other different equations with different restrictions of conditions.

Determinants of actions have been introduced for coke, bed height, bulk density and burnt lime action (Eqs. (22)–(25)) and discussed the factors affecting the equations:

(1) In any action case except bulk density the ratio of partial costs is a critical factor to decide the direction of action.

(2) In case of bed height and burnt lime actions, the coefficient of yield with respect to bed height ($\beta\eta_{H-H}$) and that of bed permeation with respect to burnt lime content ($\beta\kappa_{BL}$) are critical, respectively.

(3) In case of bulk density, however, decreasing bulk density is always favorable in cost.

Nomenclatures

- @_C, @_G, @_E, @_{BL}: Unit price of coke, COG, electricity, burnt lime (¥/t, ¥/Nm³, ¥/Kwh, ¥/t)
 %C: Coke content (mass%, raw mixture basis)
 %BL: Burnt lime content (mass%, new feed basis)
 a, b: Constants
 BTP: The strand-ward point where the flame front attains to the bottom of bed (–)
 Cost: Energy cost (¥/t)
 CR, GR, ER, VR, BLR: Unit consumption of coke, COG, electricity, air and burnt lime (kg/t, Nm³/t, Kwh/t, Nm³/t, kg/t)
 C₀: COG flow rate (Nm³/h)
 C_C, C_G, C_E, C_{BL}: Partial energy cost of coke, COG, electricity, burnt lime (¥/t)
 D_{%C}, D_H, D_{BL}, D_{ρ_m}: Determinants of coke, bed height, burnt lime, bulk density actions (¥/t)
 FFS: Flame front speed (m/h)
 H, L, W: Bed height, strand length and pallet width (m)
 PS: Pallet speed (m/h)
 P_{Sr}: Production rate (t/h)
 P_V: Suction pressure (kPa)
 V: Airflow rate (Nm³/h)
 β $\eta_{\%C}$, β η_{H-H} : Coefficients of yield with respect to coke content, bed height (–)
 β κ_{ρ_m} , β κ_{BL} : Coefficient of bed permeability with respect to bulk density, burnt lime content (–)
 c_m, c_g: Heat capacity of raw mixture, gas (J/t)
 ρ_m, ρ_g: Bulk density, gas density (t/m³)
 n: Bed permeation constant ~0.6 (–)
 κ: Bed permeability ((Nm³/h/m²)/(kPa/m)ⁿ)
 η: Yield (=sinter/raw mixture) (–)

REFERENCES

- I. Muchi and J. Higuchi: *Tetsu-to-Hagané*, **56** (1970), 371.
- S. Sato, M. Yoshinaga, M. Ichidate and T. Kawaguchi: *Tetsu-to-Hagané*, **68** (1982), 2174.
- S. Sato, T. Kawaguchi, M. Ichidate and M. Yoshinaga: *Tetsu-to-Hagané*, **70** (1984), 657.
- S. Sato, T. Kawaguchi, M. Ichidate and M. Yoshinaga: *Tetsu-to-Hagané*, **73** (1987), 804.
- S. Sato, T. Kawaguchi, M. Ichidate and M. Yoshinaga: *Tetsu-to-Hagané*, **73** (1987), 956.
- S. Sato, T. Kawaguchi, M. Ichidate and M. Yoshinaga: *Tetsu-to-Hagané*, **73** (1987), 964.
- T. Kawaguchi, S. Sato and K. Takata: *Tetsu-to-Hagané*, **73** (1987), 1940.
- J. Kano, E. Kasai, F. Saito and T. Kawaguchi: *ISIJ Int.*, **45** (2005), 500.
- T. Abe, J. Kano and M. Nakano: The 5th intern. conf. on DEM, Queen Mary University of London, London, (2010), 538.
- M. V. Ramos, E. Kasai, J. Kano and T. Nakamura: *ISIJ Int.*, **40** (2000), 448.
- K. Segawa: Ferrous metallurgical reaction engineering, Nikkan-kogyo-shinbunsha, Tokyo, (1969), Chapter 3.
- ISIJ: Tekko-binran II, Maruzen, Tokyo, (1979), 86.
- M. Nakano, Y. Hori, S. Nakano, E. Ide, S. Yoshinaga and Y. Hosotani: *Tetsu-to-Hagané*, **82** (1996), 887.
- T. Inazumi, M. Fujimoto, S. Kasama and K. Sato: *Tetsu-to-Hagané*, **77** (1991), 63.
- T. Tanaka, N. Takamatsu, T. Sato, I. Tono and Y. Sugisaki: *Camp-ISIJ*, **7** (1994), 145.
- K. Nushiro, Y. Konishi, K. Igawa, K. Takihira and N. Fujii: *Tetsu-to-Hagané*, **83** (1997), 413.
- K. Higuchi, T. Kawaguchi, M. Kobayashi, Y. Hosotani, K. Nakamura, K. Iwamoto and M. Fujimoto: *ISIJ Int.*, **40** (2000), 1188.
- K. Ichikawa, S. Machida, K. Nushiro, H. Sato and K. Takeda: *Tetsu-to-Hagané*, **92** (2006), 794.
- T. Furui, M. Kagawa, M. Kawazu, A. Sawamura, K. Sugawara, S. Uno and T. Fujiwara: *Seitetsu-kenkyu*, **288** (1976), 11797.
- M. Nagano, H. Taninaka, R. Yamamoto, M. Hattori and Y. Yamaoka: *Tetsu-to-Hagané*, **71** (1985), A173.