Estimation of Lower Limit of Fuel Rate in Blast Furnace by Mathematical Model

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Synopsis

For the purpose of estimating the fuel rate in the case that operating conditions of a blast furnace are given, an mathematical model has been developed. This model was built based upon the method which was used by Muchi et al. and the data which were taken from the recent dissection of blast furnaces were adopted, by taking account of the softening-melting zone, the melts dropping through a dead man, and the reduction of silicates by gas-metal reactions.

With the aid of this model, the fuel rate was estimated based upon the operating conditions for No. 3 blast furnace of Kimitsu Works in March, 1975. By comparing the calculated fuel rate and the actual one, the usefulness of this model has been confirmed. Further, the fuel rate has been estimated making use of the data set at a boundary condition and compared with the theoretical fuel rate which was derived by Nakatani et al.

I. Introduction

In reducing the fuel rate for blast furnace, it is necessary for stable operation to estimate the lower limit of fuel rate under predetermined operating conditions and then operate the furnace with the estimated value as a guide.

In order to estimate the fuel rate of an actual blast furnace, the operating conditions required for heating, reducing, and melting of the burden during its descent from the top to the tuyere level and reaching of the molten material to the tuyere level at a set temperature must be obtained by introducing the kinetics instead of the theory of equilibrium. The authors have developed a mathematical model for calculating the fuel rate for given furnace operating conditions. The model was established on the basis of the concept of Muchi et al. and incorporating the results of blast furnace dissection studies recently made at various steelworks. As a result, the model has the following features.

1. The softening zone in which ore becomes cohesive and larger in the apparent size and the melting zone in which the whole process from beginning to end of melting of ore occurs are assumed.

2. Slag and pig iron which pass the dead man are considered.

3. Regarding the reduction of SiO₂, the SiO gas-metal reaction is considered in addition to the slag-metal reaction.

4. Results of the blast furnace dissection study are used for deciding the values of various physical and chemical properties.

II. Outline of the Model

The burden distribution in the blast furnace is assumed as an uninclined horizontally uniform distribution. Coke and ore are charged in the form of a mixture. The space from the surface of the burden to the tuyere level is divided into four zones (lumpy, softening, melting, and dropping zones). The factors to be used in the model for each zone are as shown in Table 1. Details of the model are explained here-under according to items.

1. Reaction

1. The reduction by CO and H₂ is assumed to occur only in the lumpy zone in which the temperature of solid is below 1000°C. In other words, the CO₂ and H₂O contents of the blast furnace gas are regarded as zero when the temperature of solid is 1000°C.

2. In the softening zone and downward in which the temperature of solid is above 1000°C, the solution-loss reaction advances quickly and the atmospheric gases are only N₂, CO, and H₂.

3. The decomposition of limestone is not considered.

4. The reduction of SiO₂ is assumed to occur only in the dropping zone.

5. The carburization rate is set at 1%, at the start of melting, and the subsequent values up to the final value at tapping are linearly approximated according to the height.

2. Heat Transmission

1. In the lumpy and softening zones, coke and ore are assumed to be at the same temperature. In the melting zone, the burden materials (ore, coke, slag, and pig iron) are assumed to remain at the same temperature from beginning to end of melting of ore.

2. Although slag and pig iron are assumed to pass through the dead man, gas is assumed not to pass through it. Therefore, slag and pig iron in the dead man are assumed to be not heated and not to react. The profile of the dead man was obtained by the equations of Miyasaka et al. and Shimizu et al.

3. The gas temperature at the tuyere level is made equal to the theoretical flame temperature, which may be obtained by setting the coke preheating temperature in Ramm’s equation at 0.9 times the value of the theoretical flame temperature.

4. The temperature of solid charged at the top is set at 30°C.


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3. **Particle Size**

1. The sizes of coke and ore in the lumpy zone are assumed to remain unchanged.
2. The size of coke in the softening zone and downward is assumed to decrease to the extent of the solution-loss reaction.
3. As the size of ore in the softening zone increases due to cohesion, the following equation is applied so that the size of ore at the start of dropping becomes about 100 mm.

\[ d_o = d_{o1} + 0.0002 \cdot (t_o - 1000) \]  

(1)

4. The sizes of slag and pig iron in the dropping zone are assumed as 10 mm and 5 mm, respectively.

4. **Internal Pressure of Furnace**

Regarding the pressure on the surface of burden as the top pressure and the pressure at the tuyere level as 0.9 times the blast pressure, the internal pressures of furnace between the two levels are linearly approximated according to the height.

5. **Heat Transfer Coefficient**

The heat transfer coefficient between gas and solid or between gas and liquid is decided as follows:

1. For the lumpy zone, Ranz's equation for single sphere is used.
2. For the softening zone, the value obtained by Ranz's equation for a single sphere is multiplied by a certain correction factor so that the distance between the starting points of softening and melting (the thickness of the softening zone) becomes about 4 m. This correction factor is used as it is for the melting zone as well.
3. For the dropping zone, the value obtained by Ranz's equation for a single sphere is multiplied by another correction factor so that the coke temperature at the tuyere level becomes 0.9 times the theoretical flame temperature, the slag temperature becomes the tapping temperature +100°C and the pig iron temperature becomes the tapping temperature +50°C.

6. **Reaction Rate**

The reduction rate of iron oxide is decided as follows:

1. For the lumpy zone, a 3-interface model controlled by the chemical reaction rate is developed based on Hara’s equation. For the equilibrium constant of CO reduction, the equation proposed by Muchi et al. is used. Assuming that H₂ reduction is proportional to CO reduction, the reaction CO + H₂O ⇌ CO₂ + H₂ is assumed not to occur.
(2) For the softening and melting zones, the value obtained by the equation of Muchi et al. is multiplied by another correction factor so that the reduction ratio becomes 80~90% at the start of melting and about 95% at the start of dropping.

(3) For the dropping zone, the equation of Muchi et al. is used.

The reduction rate of SiO₂ is decided as follows:

(1) For the slag-metal reaction, the equation of Muchi et al. is used.

(2) For the SiO₂ gas-metal reaction, the SiO₂ content of coke is set at the value obtained by the following equation based on the results of dissection study on Kukioka No. 4 BF and considering that the decrease in the amount of SiO₂ due to the temperature difference means the amount of SiO₂ which was generated in the form of SiO, 60% of the value thus obtained is assumed to be absorbed into the pig iron.

\[ \text{SiO}_2 = \text{SiO}_2 + 0.00666 \cdot (t_e - 1400) \cdot 10^{-2} \]  

III. Method of Calculation

Table 2 shows the monthly average values of operating results of Kimitusu No. 3 BF for October 1974 excluding the shutdown days which is taken as the reference period.

Differential equations for the temperatures of gas, solid, and liquid in the direction of furnace height are established from the material balance and heat balance in the infinitesimal intervals of the layers based on the method of Muchi et al. Figure 1 shows a flow chart of calculation for deciding the values of furnace-wall heat transfer coefficients \( H_e \) and \( H_r \) using the data of the reference period. Figure 2 shows the calculated temperature distribution in the furnace for the reference period.

Successively, in order to estimate the fuel rate under predetermined operating conditions, the charging ratio of ore and coke (herein called the O/C) is set first, then seven algebraic equations are established using the equations for deciding the five material balances (Fe, C, H, O, and N) and the gas utilization ratios (\( \tau_{\text{CO}} \) and \( \tau_{\text{H}_2} \)), and finally the seven unknowns of top gas flow rate, top gas compositions (CO, CO₂, H₂, and H₂O), ore charging speed and coke charging speed are obtained by solving the seven equations. \( H_e \) is decided at a value that is proportional to the one raised to the 0.7 power of the top gas flow rate based on the value obtained in the reference period, while the change in the gas permeability due to the O/C difference is obtained by Ergun’s equation and the blast pressure is calculated, based on the value of the permeability change, for the predetermined top pressure. Figure 3 shows a flow chart of calculation for deciding the values of top gas temperature \( T_g \), \( H_e \), and O/C using differential equations established in

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Actual results Oct. 1974</th>
<th>Actual results Mar. 1975</th>
<th>Estimated results Mar. 1975</th>
<th>Estimated results at boundary condition</th>
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<tr>
<td>Blast temperature</td>
<td>°C</td>
<td>1275</td>
<td>1316</td>
<td>→</td>
<td>1350*</td>
</tr>
<tr>
<td>Blast humidity</td>
<td>g/Nm³-Blas</td>
<td>10.7</td>
<td>7.1</td>
<td>→</td>
<td>0.0*</td>
</tr>
<tr>
<td>Coke ash content</td>
<td>%</td>
<td>11.7</td>
<td>12.0</td>
<td>→</td>
<td>10.0*</td>
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<tr>
<td>FeO content in ore</td>
<td>%</td>
<td>6.36</td>
<td>6.54</td>
<td>→</td>
<td>0.00*</td>
</tr>
<tr>
<td>Mean size of ore</td>
<td>mm</td>
<td>19.84</td>
<td>18.71</td>
<td>→</td>
<td>18.00*</td>
</tr>
<tr>
<td>Melting temperature of ore</td>
<td>°C</td>
<td>1400</td>
<td>1400</td>
<td>→</td>
<td>1450*</td>
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<tr>
<td>Reducibility of ore</td>
<td>%</td>
<td>67</td>
<td>70</td>
<td>→</td>
<td>75*</td>
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<tr>
<td>Slag volume</td>
<td>kg/t-Pig</td>
<td>321</td>
<td>323</td>
<td>→</td>
<td>219*</td>
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<td>Blast volume</td>
<td>Nm³/min</td>
<td>6713</td>
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<td>→</td>
<td>7038</td>
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<td>Oxygen enrichment</td>
<td>Nm³/h</td>
<td>12735</td>
<td>5476</td>
<td>→</td>
<td>3000</td>
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<td>Top gas pressure</td>
<td>g/cm³</td>
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<td>2279</td>
<td>→</td>
<td>2282</td>
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<td>Fuel rate</td>
<td>kg/t-Pig</td>
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<td>Coke rate</td>
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<td>379.4</td>
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<td>370.9</td>
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<tr>
<td>Oil rate</td>
<td>kg/t-Pig</td>
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<td>65.8</td>
<td>69.4</td>
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<td>O/C</td>
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<td>4.474</td>
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<td>Production</td>
<td>t/day</td>
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<td>9,533</td>
<td>9,190</td>
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<td>Pig temperature</td>
<td>°C</td>
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<td>1,508</td>
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<td>Si content in pig iron</td>
<td>%</td>
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<td>Top gas temperature</td>
<td>°C</td>
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<td>107</td>
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<td>130</td>
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<td>CO gas utilization</td>
<td>%</td>
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<td>51.9</td>
<td>51.9</td>
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<td>Solution loss carbon</td>
<td>kg/t-Pig</td>
<td>91.9</td>
<td>97.7</td>
<td>92.7</td>
<td>95.9</td>
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<tr>
<td>Ratio of C reduction</td>
<td>%</td>
<td>31.1</td>
<td>33.0</td>
<td>31.4</td>
<td>31.5</td>
</tr>
<tr>
<td>Ratio of H₂ reduction</td>
<td>%</td>
<td>10.7</td>
<td>9.7</td>
<td>10.3</td>
<td>10.2</td>
</tr>
<tr>
<td>Ratio of CO reduction</td>
<td>%</td>
<td>58.2</td>
<td>57.3</td>
<td>58.3</td>
<td>58.3</td>
</tr>
<tr>
<td>Heat loss</td>
<td>kcal/t-Pig</td>
<td>165×10^6</td>
<td>117×10^6</td>
<td>154×10^6</td>
<td>110×10^6</td>
</tr>
</tbody>
</table>

* Data set at boundary condition.
Set initial value; Temperature & composition of top gas, burden surface & heat transfer coefficient (HW & HW')

Calculate temperature of gas & solid by Runge-Kutta-Gill method (lumpy zone)

Calculate temperature of gas, solid & melt by Runge-Kutta method (softening & melting zone)

Calculate temperature of gas, solid & melt by Runge-Kutta method (dropping zone)

Start
Set initial value; Temperature & composition of top gas, burden surface & heat transfer coefficient (HW & HW')

Calculate volume & composition of top gas, weight of coke & ore by material balance & setting O/C, ρ0 & η0

Calculate temperature of gas & solid by Runge-Kutta-Gill method (lumpy zone)

Calculate temperature of gas, solid & melt by Runge-Kutta method (softening & melting zone)

Calculate temperature of gas, solid & melt by Runge-Kutta method (dropping zone)

Start

Fig. 1. Flow chart of fuel rate calculation (reference period).

Fig. 2. Flow chart of calculation (at boundary condition).

Fig. 3. Flow chart of calculation (at boundary condition).

IV. Verification of Appropriateness of the Model and Example of Estimation of the Lower Limit of Fuel Rate

In order to verify the appropriateness of the model, the fuel rate of Kimitsu No. 3 BF was estimated using the monthly average values of operating results for March 1975 excluding the shutdown days (shown in Table 2). The results were as shown in Table 2. The estimated fuel rate for March was 440.3 kg/t-Pig, which proved to be 9.8 kg/t-Pig higher than the actual value (shown also in Table 2). The conceivable reason for this difference is that, although this model assumes the blast furnace as a uniform system without considering burden radial distribution, the actual blast furnace operation permits adjustment of the burden radial distribution for controlling the gas flow and raising the gas utilization ratio by reducing the heat loss in the lower portion of the furnace shell and increasing the chances of gas-ore contact in the upper portion of the furnace, thereby further reducing the fuel rate.

Successively, the authors estimated the fuel rate under certain boundary operating conditions. Operating conditions which were considered to be realizable in the future are shown by asterisk in Table 2. Of these conditions, the raw material properties were decided as follows based on the properties of self-fluxing pellet.

(1) Chemical composition: T.Fe = 60%, SiO2 = 3.8%, CaO/SiO2 = 1.47 (hematite ore)
(2) Melting temperature: 1450°C
(3) Reduction ratio: 75% (JIS method)
(4) Average particle size: 18 mm

The blast conditions were decided so that the theoretical flame temperature would become 2350°C. As shown in Table 2, the estimated fuel rate was 396.5 kg/t-Pig. The calculated temperature distribution in the furnace is shown in Fig. 4. The softening zone is lower and the melting temperature is higher compared with the value calculated for the reference period. In order to attain this lower limit of fuel rate, techniques for producing raw materials with the above properties must be established and the permeability enabling O/C = 4.75 must be assured.
was obtained. This value was compared with an estimated value of theoretical fuel rate by Nakatani et al.

REFERENCES


Appendix 1

Differential equations for the temperatures of gas, solid, and liquid in the direction of furnace height for every zone are as follows:

(1) Lumpy zone

\[
dT/dz = \left[ 6(1-\varepsilon)H_A(T-t)/d\phi + 22.4q_1A_1(C_{pp} - C_{pv} + r(C_{pv} - C_{p})) \right] + 0.5q_2A_1 + \pi D_4H_w \\
\times (T - t_0)/C_{fg} 
\]

\[
dt/dz = \left[ 6(1-\varepsilon)H_A(T-t)/d\phi - q_3A_1(1+r) \right] \\
- 0.5q_2A_1/C_{st,F} 
\]

\[
q_1 = R^*_{coh} + R^*_{com} + R^*_{cw} 
\]

\[
q_2 = R^*_{coh} - 12.642 - 2.816r + R^*_{com}(6.246 + 16.108r) \\
+ R^*_{cw}(3.330 + 6500r) 
\]

\[
q_3 = R^*_{coh}(2 \times 231.55p_m - 3 \times 159.7C_{p}) \\
+ R^*_{com}(3 \times 71.85C_{pv} - 231.55C_{p}) + R^*_{cw} \\
\times (55.85C_{st} - 71.85C_{st}) 
\]
(2) Softening zone
$$dT/dz = (6(1-\varepsilon)H_pA(t-t)/d \cdot \phi + 22.4R_{cow} A_{Cpg} T + 0.5 \times 34.846 R_{cow} A_4 + \pi D_4 H_p (T-t) - q_A t - 0.5 \times 34.846 R_{cow} A_4)/C_{pg} F_g$$
$$dt/dz = (6(1-\varepsilon)H_pA(t-t)/d \cdot \phi + 12R_{cow} A_4 / C_4)$$
$q_t = R_{cow}(55.85 C_{pg} - 71.85 C_{pg})$

(3) Melting zone
$$dT/dz = (6(1-\varepsilon)H_pA(t-t)/d \cdot \phi + A_4 H_p + A_p H_p)$$
$$(T-t_m) + 22.4 R_{cow} A_4 C_{pg}(T-t_m) / C_{pg} F_g$$
$$dt/dz = (6(1-c)H_p A_4 (T-t)/d \cdot \phi + A_4 H_p + A_p H_p)$$

(4) Dropping zone
$$dT/dz = (6(1-\varepsilon)H_pA(t-t)/d \cdot \phi + A_4 H_p + A_p H_p)$$
$$(T-t_d) + 22.4 R_{cow} A_4 C_{pg}(T-t_d) / C_{pg} F_g$$
$$dt/dz = 0$$

(5) O balance:
$$F_g(2x + 2y + v)x \times 12/22.4 = F_{\delta}(12.6 + \tilde{\beta})x \times 32/22.4$$
$$+ F_{\delta}(60 + \beta)W \times 16/18 000 + \alpha F_p x 16/12 000$$
$$+ F_{\delta} [O] + 0.4297F_{Fe} - F_{Fe} x 16/55.85$$

(6) N balance:
$$F_{\delta}(1-x-y-u-v) = 60F_{\delta} x 0.79 + F_{\delta} N_e x 22.4/28$$

Appendix II
Seven algebraic equations are established using the equations for deciding the five material balances and the two gas utilization ratios. The seven unknowns of top gas flow, top gas compositions, ore charging speed, and coke charging speed are obtained by solving the seven equations.

Seven algebraic equations are as follows:

(1) Fe balance:
$$F_{\delta}[Fe] + F_{Fe} = F_{\delta}[Fe] + F_{Fe}$$

(2) C balance:
$$F_p = (x + y) x 12/22.4 = F_{\delta}(12.6 + \tilde{\beta})x \times 32/22.4$$
$$+ F_{\delta}(60 + \beta)W \times 16/18 000 + \alpha F_p x 16/12 000$$
$$+ F_{\delta} [O] + 0.4297F_{Fe} - F_{Fe} x 16/55.85$$

(3) N balance:
$$F_{\delta}(1-x-y-u-v) = 60F_{\delta} x 0.79 + F_{\delta} N_e x 22.4/28$$

Nomenclature
$A_z$: Cross section of the furnace at the level z (m²)
$A_{SL}, A_{PI}$: Surface areas of slag and pig iron in the dropping zone (m²/m³ (bed))
$C_{Fe}, C_{CO}, C_{CO_2}, C_{H_2}, C_{H_2O}$: Specific heats of blast furnace gas, CO, CO₂, H₂, and H₂O gas (kcal/
Carbon contents in coke, oil, and pig iron

Specific heats of solid (in the lumpy and softening zones), hematite, magnetite, wüstit, metal, coke, slag, and pig iron (kcal/kg·deg)

Particle diameters of solid (in the lumpy and softening zones), ore, coke, ore before charging, slag, and pig iron (m)

Mass flow rates of solid (in the lumpy and softening zones), ore, coke, slag, and pig iron (kg/h)

Blast furnace gas flow rate (Nm³/h)

Blast volume (Nm³/min)

Oil injection rate (l/h)

Oxygen enriched flow rate (Nm³/h)

Iron contents in ore, coke, slag, and pig iron

Heat transfer coefficients of gas-solid (in the lumpy and softening zones), gas-coke, gas-slag, and gas-pig iron (kcal/m²·h·deg)

Furnace-wall heat transfer coefficient in the lumpy, softening, and melting zones (kcal/m²·h·deg)

Furnace-wall heat transfer coefficient in the dropping zone (kcal/m²·h·deg)

Hydrogen contents in coke and oil

Proportional constant in the equation for deciding $\eta_{co}$ (Nm³/kg)

Manganese content in pig iron

Nitrogen content in coke

Oxygen content in ore

Phosphorous content in pig iron

H₂O and CO₂ ratio in top gas

Proportional constant in the equation concerning $T_jel$ and $T_{co}$

Reduction rates of hematite, magnetite, and wüstit by CO and reduction rate of SiO₂ (kg mol (CO)/m³ (bed)·h, kg mol (SiO₂)/m³ (bed)·h)

Slag volume (kg/t-Pig)

Silicon content in pig iron

SiO₂ in coke before charging

Temperatures of blast furnace gas and top gas (°C)

Titanium content in pig iron

Dropping velocities of slag and pig iron in the dropping zone (m/min)

H₂ content in top gas

H₂O content in top gas

Blast humidity (g/Nm³-Blast)

Coke ash content

CO content in top gas

Distance from stock level (m)

Distance from the melting start point to tuyere level (m)

Ore and coke charging ratio (O/C)

Void

Density of oil (kg/l)

Densities of slag and pig iron (kg/m³)

Shape factor of particle

Utilization ratios of CO and H₂ gas