Maximum Rates of Pulverized Coal Injection in Ironmaking Blast Furnaces

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(Received on January 7, 2011; accepted on April 18, 2011)

A theoretical study is made on the maximum injection rates of pulverized coal in ironmaking blast furnaces. The study takes account of two restrictive conditions which enable stable blast furnace operations to be maintained. One is to burn out the injected coal in the raceway zone and the other is to avoid the coal ash deposition on the blowpipe wall. The predicted maximum injection rates for some operating blast furnaces are about 190–210 kg per ton of pig-iron produced, which seem to be reasonable in comparison with experiences reported. Also, the influences of pulverized coal injection on the coke consumption, the production rate of pig-iron and the bosh gas temperature are examined in relation to some blast gas conditions such as the oxygen enrichment and the moisture addition.

KEY WORDS: ironmaking; pulverized coal injection; blast furnace; coal combustion; coke combustion; reduction of iron ore; solution loss reaction.

1. Introduction

Use of pulverized coal as a supplementary fuel in ironmaking blast furnaces is of great importance for global requirements such as energy saving and environmental protection.1,2) In the early 1980th, the pulverized coal injection (PCI) rates were only 50–60 kg/t-p (kg per ton of pig-iron produced) and then went up to 150–200 kg/t-p.3–7) Some blast furnaces in the later 1990th attempted the injection rates greater than 200 kg/t, near maximum.2) Simultaneously, PCI related problems were experienced, e.g., Ostrowski8) reported severe tuyere failures, furnace hanging and so on encountered in the USA. Also, Abe9) et al. pointed out possibility of fused ash build-ups in the blowpipe walls.

A number of studies were carried out on how to increase the PCI rate without causing instability in furnace operations. Matsui et al.10) demonstrated the validity of applying the centre coke charging technology with a double lance injection system. Concerning the permeability in the lower part of a blast furnace, Yamaguchi et al.11,12) examined the behavior of fine coal and coke materials produced in the raceway zone, i.e., how they accumulated in the burden region to worsen the permeability. Ohno et al.13) reported the effect of mixing of pulverized coal with oxygen on the coal combustion in the raceway region using various coal injection burners. Injection lance positions relative to the tuyere nose3,9,14) and types of injection lances6,10,15) were also tested to enhance the combustion of coal or to minimize the pressure drops within the blowpipe-tuyere zone.

Although such great efforts have been made elsewhere, only empirical information is available on how much pulverized coal can be injected for various blast furnace conditions or how blast furnace performances are affected when increasing the PCI rate toward a maximum value. As a first step to clarify these, the authors16,17) have developed a simple model of the coal combustion in the blowpipe-tuyere-raceway region. Based on the coal combustion model, the present study attempts predicting the maximum rate of PCI. It is also an intention of the study to elucidate the blast furnace performance represented by the coke consumption, the pig-iron production rate and the bosh gas temperature in relation to the PCI rate and some blast gas conditions such as the oxygen enrichment and the moisture addition.

2. Theoretical

To succeed in operating the PCI systems, attention must be paid to various phenomena occurred in the blast furnace, some of which are as follows.

(1) Combustion degree of injected coal or behavior of unburned coal fines in the coke bed affecting the gas flow distribution in the burden region.

(2) Behavior of fused coal ash or possibility of its deposition in the blowpipe-tuyere zone.

(3) Permeability or gas flow distribution in the burden zone affected by the ore/coke ratio increasing with increasing the coal injection rate.

(4) Thermal properties represented by the bosh gas temperature or the heat flow ratio affecting reactions occurred in the lower part of the blast furnace.

Of these items, Abe et al.9) demonstrated the importance of items (1) and (2) when determining the position of injection lance. Referring to their consideration, the present theory provides two restrictive conditions concerning items (1) and (2). One is to combust completely the injected coal within the raceway zone and the other is to avoid the coal ash deposit in the blowpipe end. Then, two critical coal injection rates are obtained corresponding to these restric-
tive conditions. The theoretical maximum injection rate is defined to be the smaller one.

Regarding item (4), the adiabatic flame temperature of bosh gas is examined in relation to the PCI rate and some blast gas conditions. Item (3) is not dealt with in the present analysis as the flow distribution may be adjustable or improved to some extent by modifying the solid material distribution in the burden region.\(^{19}\)

### 2.1. Models of Coal and Coke Combustions and Reduction of Iron Ore

Pulverized coal is injected into hot blast gas in the blowpipe zone, being ignited and combusted. As illustrated in Fig. 1, the coal ignition in the warm-up zone followed by the combustions in the blowpipe-tuyere and raceway zones has been modeled and analyzed previously,\(^ {16,17}\) which is utilized in the present study. In the blowpipe-tuyere zone, the coal combustion is dominated by reaction 1 listed in Table 1 and reactions 1 and 2 may occur in the raceway zone. As to the coke combustion in the raceway zone, reactions 4 and 5 are taken into account.

Phenomena occurred inside the blast furnace such as the coke consumption and the reduction of iron ore are analyzed in Appendix A referring to the reviews of Tate\(^ {18}\) and Muchi.\(^ {19}\) The analysis is based on the flow diagram of gas species concerned, drawn in Fig. 2, and the chemical reactions listed in Table 1.

In the process of the CO generation, the overall gasification of coke (\(W_{c}C\) due to reaction 6), the solution loss (\(W_{c}O\) due to reactions 5 and 7) and the direct reduction (\(W_{f}F\) due to reaction 11) as well as the overall gasification of coal (\(W_{f}C\) due to reaction 3) are taken into account. For the \(H_{2}\) gas generation, the decomposition of added moisture (reaction 8) and the overall gasification of coal (reaction 3) as well as the solution loss by \(H_{2}O\) gas (reaction 7) are considered.

Of the resultant mole rates of \(CO\) and \(H_{2}\) gases generated, \(n_{CO}\) and \(n_{H_{2}}\), the fractions denoted as \(\sigma_{CO}\) and \(\sigma_{H_{2}}\) are utilized for the indirect reduction of iron ore. Variables \(\sigma_{CO}\) and \(\sigma_{H_{2}}\) are related to the conventionally defined \(CO\) and \(H_{2}\) utilization parameters of \(\eta_{CO}\) and \(\eta_{H_{2}}\) (see Eqs. (A-17)–(A-20) in Appendix A). The rest of the iron ore oxygen, the fraction of which is denoted as \(\lambda_{s}\), is reduced directly by coke carbon in this model. Other symbols for the variables used in Fig. 2 are referred to in Nomenclature.

### 2.2. Burnout Index

The burnout index \(I_{BO}\), is defined as,

\[
I_{BO} = \frac{\theta_{B}}{\theta_{R}} \hspace{1cm} (1)
\]

where \(\theta_{B}\) is the time period required for unburned coal entering the raceway to burn out completely under the raceway conditions (see Eq. (22) in Ref. 17) and \(\theta_{R}\), the residence time of the coal in the raceway zone, is obtained as the volume of the raceway cavity divided by the volume rate of the blast gas (see Eq. (13) in Ref. 17).

When \(I_{BO}\) is greater than unity, meaning that the time required for the complete combustion of coal is longer than the residence time in the raceway zone, unburned fine par-

### Table 1. Chemical reactions considered in the present study.

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction formula</th>
<th>(\Delta H, \text{J/mol})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Complete combustion of coal (CH_{m}O_{n} + n_{i}O_{2} \rightarrow CO_{i} + 0.5m_{i}H_{2}O) where (n_{i} = 1 + 0.25m_{i} - 0.5m_{2})</td>
<td>(\Delta H_{1} = -Q_{m_{1}})</td>
</tr>
<tr>
<td>2</td>
<td>Gasification of coal by (CO_{2}) (CH_{m}O_{n} + CO_{2} \rightarrow 2CO + 0.5m_{i}H_{2}) where (n_{2} = 0.5(1 - m_{2}))</td>
<td>(\Delta H_{2} = \Delta H_{1} - 2(\Delta H_{1} - \Delta H_{2}) + 0.5m_{i}H_{4})</td>
</tr>
<tr>
<td>3</td>
<td>Overall gasification of coal (CH_{m}O_{n} + n_{i}O_{2} \rightarrow CO + 0.5m_{i}H_{2}) where (n_{2} = 0.5(1 - m_{2}))</td>
<td>(\Delta H_{3} = \Delta H_{1} + (\Delta H_{1} - \Delta H_{2}) + 0.5m_{i}H_{4})</td>
</tr>
<tr>
<td>4</td>
<td>Complete combustion of coke (C(s) + O_{2} \rightarrow CO)</td>
<td>(\Delta H_{4} = -0.394 \times 10^{6})</td>
</tr>
<tr>
<td>5</td>
<td>Solution loss of coke by (CO_{2}) (C(s) + CO_{2} \rightarrow 2CO)</td>
<td>(\Delta H_{5} = 0.174 \times 10^{6})</td>
</tr>
<tr>
<td>6</td>
<td>Overall gasification of coke (C(s) + 0.5O_{2} \rightarrow CO)</td>
<td>(\Delta H_{6} = -0.110 \times 10^{6})</td>
</tr>
<tr>
<td>7</td>
<td>Solution loss of coke by (H_{2}O) (C(s) + H_{2}O \rightarrow CO + H_{2})</td>
<td>(\Delta H_{7} = 0.132 \times 10^{6})</td>
</tr>
<tr>
<td>8</td>
<td>Decomposition of moisture (H_{2}O(gas) \rightarrow H_{2} + 0.5O_{2})</td>
<td>(\Delta H_{8} = 0.242 \times 10^{6})</td>
</tr>
<tr>
<td>9</td>
<td>Indirect reduction by (CO) ((1/3)Fe_{2}O_{3} + CO \rightarrow (2/3)Fe + CO_{2})</td>
<td>(\Delta H_{9} = -0.899 \times 10^{4})</td>
</tr>
<tr>
<td>10</td>
<td>Indirect reduction by (H_{2}) ((1/3)Fe_{2}O_{3} + H_{2} \rightarrow (2/3)Fe + H_{2}O)</td>
<td>(\Delta H_{10} = 0.322 \times 10^{5})</td>
</tr>
<tr>
<td>11</td>
<td>Direct reduction (FeO + C(s) \rightarrow Fe + CO)</td>
<td>(\Delta H_{11} = 0.156 \times 10^{6})</td>
</tr>
</tbody>
</table>
articles are possibly stuck into the interstices of the coke bed. This could cause changes in the gas stream distribution in the lower part of the blast furnace. Therefore, \( I_{BO} \) must be less than unity for good PCI operations.

### 2.3. Ash Deposition Index

To assess the possibility of the ash deposition, the blowpipe wall upstream of the tuyere is considered to be severer than the tuyere wall as the surface temperature of the tuyere pipe wall upstream of the tuyere may be well below 773 K due to water cooling. The ash deposition index, \( I_{AD} \), is defined as

\[
I_{AD} = \frac{T_{BL}}{T_{af}} \quad \text{......................... (2)}
\]

where \( T_{BL} \) is the blast gas temperature at the blowpipe end or the boundary between blowpipe and tuyere and \( T_{af} \) is the ash fusion temperature. Taking the mass and energy balances in the blast gas with the coal combustion, \( T_{BL} \) is derived as \( T_A(\theta_b) \) (see Eq. (15) in Ref. 16). In the ideal gas law and a model of heterogeneous ignition and diffusion controlled combustion of coal are assumed.

The value of \( I_{AD} \) greater than unity means that the coal ash is possibly fused and trapped on the blowpipe wall as the gas temperature at the blowpipe end is higher than the ash fusion temperature.

### 2.4. Maximum Coal Injection Rate

From Eq. (1), the condition of \( I_{BO} = 1 \) gives a critical coal injection rate, denoted as \( F_{BO} \) with a unit of kg/t-p. Another critical coal injection rate, denoted as \( F_{AD} \), is obtained corresponding to the condition of \( I_{AD} = 1 \) in Eq. (2). The theoretical maximum injection rate with no ash deposition nor change in the gas flow distribution due to unburned coal fines trapped in the coke bed is either \( F_{BO} \) or \( F_{AD} \), the smaller one.

Note that the coal injection rate is denoted as either a capital letter \( F \) or a small letter \( f \), i.e., \( F \) means the mass of coal injected per ton of pig-iron produced (kg/t-p) and \( f \) is the mass of coal injected per unit time (kg/s). To convert from \( f \) to \( F \), the mass of pig-iron produced per unit time, denoted as \( f_{Fe} \) in kg/s (or \( F/Fe \) in t/s), is needed and its derivation is explained in Appendix A.

### 3. Results and Discussion

#### 3.1. Conditions for Calculations

Operating data used in the calculations are listed in Table 2 for some blast furnaces with PCI practices in the mid 1980s. Some parameters needed in the calculations are specified or assumed as follows.

1. \( \lambda_0 \), the fraction of the iron ore oxygen directly reduced appeared in Eqs. (A-11) and (A-12), is assumed to be 0.25 as the calculated \( \lambda_0 \) were shown to be in a range of 0.2 and 0.35 by Muchi\(^{19}\) and in a range of 0.15 and 0.25 by Miyasaka et al.\(^{21}\).
   
2. For both \( \eta_{co} \) and \( \eta_{dr} \) appeared in Eqs. (A-17) and (A-18), the value of 0.5 is assumed. According to Tate,\(^{18}\) the values of \( \eta_{co} \) are near 0.5 for modern blast furnaces.
3. For \( T_{sbl} \) appeared in Eq. (A-32), the value of 443 K is assumed.\(^{22}\)
4. For \( q_{Li} \) in Eq. (A-35), the value of 29.3 \( \times 10^4 \) kJ/t-p shown by Tate\(^{19}\) is adopted.
5. For \( T_{pig} \) and \( q_{pe} \) appeared in Eq. (A-37), \( T_{pig} \) is assumed to be 1773 K and \( q_{pe} \) is assumed to be 133.6 \( \times 10^4 \) kJ/t-p.\(^{22}\)
6. With respect to the value of \( Q_{slag} \) in Eq. (A-42), the following reported value\(^{23}\) is assumed, i.e., \( Q_{slag} = 196.7 \times 10^5 \) kJ/t-p.

#### Table 2. Operating conditions for some blast furnaces.

<table>
<thead>
<tr>
<th>BF No</th>
<th>VB Nm³/s</th>
<th>TB K</th>
<th>PB kPa</th>
<th>H₂O kg/Nm³</th>
<th>O₂ kg/Nm³</th>
<th>F kg/t-p</th>
<th>Coal type</th>
<th>f iron kg/s</th>
<th>FBO kg/t-p</th>
<th>FAD kg/t-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>104.3</td>
<td>1428</td>
<td>471</td>
<td>0.0320</td>
<td>0.0000</td>
<td>58.0</td>
<td>A</td>
<td>86.5</td>
<td>203</td>
<td>317</td>
</tr>
<tr>
<td>2</td>
<td>95.5</td>
<td>1423</td>
<td>491</td>
<td>0.0310</td>
<td>0.0000</td>
<td>62.0</td>
<td>A</td>
<td>78.0</td>
<td>206</td>
<td>317</td>
</tr>
<tr>
<td>3</td>
<td>89.7</td>
<td>1338</td>
<td>476</td>
<td>0.0400</td>
<td>0.0000</td>
<td>59.0</td>
<td>A</td>
<td>72.6</td>
<td>213</td>
<td>331</td>
</tr>
<tr>
<td>4</td>
<td>111.7</td>
<td>1448</td>
<td>473</td>
<td>0.0250</td>
<td>0.0000</td>
<td>53.0</td>
<td>A</td>
<td>95.3</td>
<td>201</td>
<td>311</td>
</tr>
<tr>
<td>5</td>
<td>117.0</td>
<td>1468</td>
<td>481</td>
<td>0.0310</td>
<td>0.0000</td>
<td>50.0</td>
<td>A</td>
<td>89.2</td>
<td>202</td>
<td>312</td>
</tr>
<tr>
<td>6</td>
<td>96.7</td>
<td>1453</td>
<td>475</td>
<td>0.0200</td>
<td>0.0000</td>
<td>70.0</td>
<td>B</td>
<td>89.1</td>
<td>188</td>
<td>288</td>
</tr>
<tr>
<td>7</td>
<td>62.1</td>
<td>1431</td>
<td>451</td>
<td>0.0155</td>
<td>0.0263</td>
<td>59.1</td>
<td>C</td>
<td>55.5</td>
<td>194</td>
<td>293</td>
</tr>
<tr>
<td>8</td>
<td>45.3</td>
<td>1432</td>
<td>320</td>
<td>0.0113</td>
<td>0.0187</td>
<td>43.2</td>
<td>C</td>
<td>53.2</td>
<td>186</td>
<td>194</td>
</tr>
</tbody>
</table>

The values of \( X_b \) are not shown because of secrecy requested.

<table>
<thead>
<tr>
<th>Coal</th>
<th>Dpo µm</th>
<th>Qs MJ/kg</th>
<th>C dry-%</th>
<th>H dry-%</th>
<th>O dry-%</th>
<th>Ash dry-%</th>
<th>VM dry-%</th>
<th>AFT* K</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>50</td>
<td>27.05</td>
<td>72.5</td>
<td>4.5</td>
<td>10.5</td>
<td>10.0</td>
<td>33.0</td>
<td>1963</td>
</tr>
<tr>
<td>B</td>
<td>40</td>
<td>29.8</td>
<td>77.3</td>
<td>4.7</td>
<td>8.6</td>
<td>7.3</td>
<td>33.0</td>
<td>1973</td>
</tr>
<tr>
<td>C</td>
<td>40**</td>
<td>33.4</td>
<td>82.2</td>
<td>5.3</td>
<td>10.8</td>
<td>6.1</td>
<td>37.2</td>
<td>1788</td>
</tr>
</tbody>
</table>

* AFT = Ash Fusion Temperature **: assumed value

\[
M_o = \frac{3}{2m_{co}} \times 1000 = \frac{3}{0.05585 \times 2} \times 1000 = 26.86 \times 10^4 [mol \ l^{-1} \ p^{-1}]
\]
An overview flowchart to calculate $F_{BO}$ and $F_{AD}$ is depicted in Fig. 3. The calculation starts with reading the input parameters of the blast gas conditions, the blowpipe geometry, the material properties of coal, coke and iron ore and the furnace properties noted above in (1)–(6). With respect to $F_{BO}$, assuming the value of $f$, the coal injection rate in kg/s, is repeated until the satisfactory conversion is attained in Eq. (1) for $IBO = 1$, i.e., $\theta_R = \theta_a$, and then in the program of coke consumption and iron ore reduction the production rate of pig-iron $Fe$ is evaluated. Thus obtained $f$ value divided by the $Fe$ value results in $F_{BO}$. As to $F_{AD}$, Eq. (2) for $IAD = 1$, i.e., $T_{BL} = T_{af}$, is used to converge the $f$ value and then the corresponding $Fe$ value is again obtained to convert to $F_{AD}$. Simultaneously, the following output parameters are evaluated, the coke consumption rates expressed by $WC_t$, $WC_s$, $WC_d$, $WC_p$ and $WC_{si}$, the mole fractions of $CO$ and $H_2$ utilized for indirect reduction, $\sigma_{CO}$ and $\sigma_{H_2}$, the fraction of iron ore oxygen removed by $CO$ to total indirectly reduced oxygen, $\lambda_{CO}$, and the mole rates of gas species noted in Fig. 2.

### 3.2. Production Rate of Pig-iron

Before discussing the maximum coal injection rates, the mass rate of pig-iron produced $f_{iron}$ is examined. The calculated $f_{iron}$ values are plotted against the corresponding data of the blast furnaces in Fig. 4. Agreement between the predictions and the data seems to be fairly well. This implies the assumed constant values for $\eta_{CO}$ and $\eta_{H_2}$ (see Sec. 3.1. (2)) are reasonable as the mean values. That is, $\eta_{CO}$ and $\eta_{H_2}$ showing the degrees of $CO$ and $H_2$ utilizations for reduction affect greatly the amount of iron ore reduced.

### 3.3. Maximum Coal Injection Rates

For the blast furnaces shown in Table 2, $F_{AD}$ and $F_{BO}$ values are calculated and listed in the table. The smaller ones are the maximum coal injection rates predicted, which are about 190–210 kg/t-p. Although there are no data available to confirm the calculations, the maximum values predicted are considered to be reasonable in the order of magnitude, judging from the review paper and the report of Tamura et al. who estimated a value of 180 kg/t-p for the case they investigated.

### 3.4. Sensitivity Analysis of the Theory

A series of sensitivity tests are conducted using the operating conditions of BF No.4 in Table 2 as a base. Firstly, the effects of the coal injection rate $F$ on the production rate of pig-iron and the consumption rate of coke are tested. Then, the moisture addition, the oxygen enrichment, the injection lance position and the coal particle size are examined in their effects on the maximum coal injection rate.

#### 3.4.1. Coal Injection Rate

As depicted in Fig. 5, the mass rate of pig-iron produced $f_{iron}$ is increased with increasing $F$. The reason is that injecting more coal (or replacing more coke by coal), the mole...
rates of the reducing gases, CO and H₂ generated, are greater as the coal includes hydrogen and oxygen. This also results in the less amount of the total fuel (the sum of coal and coke) consumed per ton of pig-iron produced. In Fig. 6, the variations of \( W_{C_t} \) and \( W_{C_s} \) with \( F \) are displayed. The injected coal is seen to replace the coke carbon gasified more than that consumed by solution loss. In Fig. 7, the bosh gas temperature is shown to decrease with increasing \( F \). This is due to the replacement of coke by coal releasing less heat of gasification.

3.4.2. Moisture Addition

Figure 8 shows the maximum coal injection rates in relation to the moisture addition where the chain line (the alternate long and short dash line) is for \( I_{BO} = 1 \) (i.e., \( F_{BO} \)) and the dotted line is for \( I_{AD} = 1 \) (i.e., \( F_{AD} \)). The moisture addition in this range is ineffective for both \( F_{BO} \) and \( F_{AD} \) as well as for the coke consumption rate and the pig-iron production rate seen in Fig. 9. Obviously, the bosh gas temperature, as shown in Fig. 10, is decreased with increasing moisture due to the endothermic properties of the moisture vaporization and decomposition.

Despite the decrease in the bosh gas temperature, the value of \( F_{BO} \) is not decreased. The reasons are that the residence time of coal particles in the raceway is longer due to the enlargement of the raceway cavity caused by the gas mole increase of the blast and also that the mean oxygen content in the raceway is more or less increased as moisture includes oxygen.

With respect to \( f_{\text{loss}} \), its value is almost unchanged. The effect of the decreased bosh gas temperature is compensated...
by the increase in the reducing gases generated with increasing the moisture added.

3.4.3. Oxygen Enrichment

In Fig. 11, the oxygen enrichment is shown to be slightly effective to raise the maximum coal injection rates as the oxygen enrichment enhances the combustion rate of coal. Further, the more oxygen enriched, the more reducing gases generated with more heat released, resulting in the increase of pig-iron produced as shown in Fig. 12 and the increase of bosh gas temperature in Fig. 13. However, the total fuel rate is increased with increasing the oxygen enriched. The reason is that the sensible heat of the produced pig-iron is increased as the pig-iron temperature is increased. In other words, to produce a ton of pig-iron requires more heat, resulting in the more fuel consumed. The value of $F_{AD}$ is slightly increased with increasing the oxygen enriched as the blast gas temperature is lowered after mixing the oxygen under the constant temperature of dry blast air.

The oxygen enrichment may be effectively used to compensate the lowered bosh gas temperature when injecting coal (see Fig. 7) or adding moisture (see Fig. 10).

3.4.4. Injection Lance Position

The injection lance position $X_b$, the distance between the lance position and the blowpipe end, is examined using the calculated results shown in Fig. 14. Increasing $X_b$ greater than 0.3 m, the slope of $F_{AD}$ declines greatly whereas the increase of $F_{RO}$ is very small. The gas temperature at the blowpipe end increases with increasing $X_b$ and reaches the ash fusion temperature at $X_b$ equal to about 0.3 m unless $F_{AD}$ is decreased. The decrease of $F_{AD}$ for $X_b > 0.3$ m is to keep the gas temperature below $T_{af}$ at the blowpipe end.

A longer distance of $X_b$ seems to give rise to a greater possibility of the ash deposition rather than improving the combustion of coal. Therefore, lance positions closer to tuyeres are preferable depending on the properties of coal injected. This has been applied elsewhere (Ohsuzu et al., Tamura et al.).

3.4.5. Coal Particle Size

The coal particle size affects greatly on the maximum injection rate as shown in Fig. 15. The larger particle size

![Graph](image1)

Fig. 11. Effects of $O_2$ enrichment on maximum coal injection rates corresponding to burnout and ash deposition indices.

![Graph](image2)

Fig. 12. Effects of $O_2$ enrichment on pig-iron production rate and coke and total fuel consumption rates.

![Graph](image3)

Fig. 13. Effect of $O_2$ enrichment on bosh gas temperature.

![Graph](image4)

Fig. 14. Effects of injection lance position on maximum coal injection rates corresponding to burnout and ash deposition indices.

![Graph](image5)

Fig. 15. Effects of coal particle size on maximum coal injection rates corresponding to burnout and ash deposition indices.
4. Conclusion

The present study has attempted predicting the maximum coal injection rates. Consequently, the following results are obtained.

(1) The predicted maximum coal injection rates for some blast furnaces are about 190–210 kg/t, which seem to be reasonable judging from reported experiences.

(2) To replace coke by coal increases the overall mole rates of CO and H₂ gases generated whereas the bosh gas temperature is lowered.

(3) The moisture addition and the oxygen enrichment are ineffective to increase the maximum coal injection rate. However, the oxygen enrichment raises the bosh gas temperature, which is effectively used to adjust the lowered bosh gas temperature by injecting coal or adding moisture.

(4) Injection lances located relatively closer to tuyeres are possible to avoid the ash deposition on the blowpipe-tuyere region, which may affect little to worsen the burnout property of injected coal.

(5) The particle size is quite effective for the maximum coal injection rate.

(6) The results of the sensitivity tests on the whole indicate that the maximum coal injection rates are dominated or determined by \( F_{BO} \) rather than \( F_{AD} \). In the ranges of the lance position and the coal properties examined, the risk of the ash deposition is said to be small. Of course, it must be cautious about the ash deposition risk when the distance \( X_0 \) is relatively long or coals with relatively low ash fusion temperatures are injected.

Further studies are needed for assumptions adopted in the present calculations, e.g., constant values assumed for parameters \( \lambda_{dr} \), \( \eta_C \), and \( \eta_H \). Also, it is important in the future to clarify the effects of the ore/coke ratio varying with the coal injection rate on the permeability or the gas flow distribution.

Nomenclature

\( C_i \): mean value of oxygen content in blowpipe zone, –

\( C_i' \): initial oxygen content in blast gas, –

\( C_{pig} \): specific heat of pig-iron, J/(kg K)

\( C_i\): mean value of \( O_i \) content in raceway, –

\( D_{pig} \): diameter of coal particle, m

\( F \): pulverized coal injection rate, kg/t-p

\( F_{BD} \): critical coal injection rate at \( I_{BD} = 1 \), kg/t-p

\( F_{BO} \): critical coal injection rate at \( I_{BO} = 1 \), kg/t-p

\( F_C \): mass of pig-iron produced per unit time, ton/s

\( f \): mass of pulverized coal injected per unit time, kg/s

\( f_{C0} \): mass fraction of slag in coke, –

\( f_{C0} \): mass fraction of slag in iron ore, –

\( f_{pig} \): mass of pig-iron produced per unit time, kg/s

\( \Delta T_i \): heat of reaction \( i \) listed in Table 1, J/mol

\( I_{BD} \): ash deposition index, –

\( I_{BO} \): burnout index, –

\( J_{C0}, J_{C0} \): constants defined in Eq. (A-32), J/kg

\( J_{C} \): constant defined in Eq. (A-33), J/kg

\( J_{C0} \): constant defined in Eq. (A-41), J/t-p

\( J_i \): constant defined in Eq. (A-24), kg/m³

\( J_{2} \): constant defined in Eq. (A-26), mol/t-p

\( J_3 \), \( J_4 \), \( J_5 \), \( J_6 \), \( J_7 \): constants defined in Eqs. (A-28), (A-29), (A-33), (A-35), (A-41), J/kg

\( J_8 \) and \( J_{9} \): constants defined in Eq. (A-43), J/kg

\( M_{O} \): mole of iron ore oxygen per unit ton of pig-iron produced, mol/t-p

\( m_{C0} \), \( m_{C0} \), \( m_{H2O} \) and \( m_{O} \): molecular weights of carbon, coal, \( H_2O \) and \( O_2 \), kg/mol

\( n_{CO} \), \( n_{H2O} \): mole flow rates of \( N_2, H_2O, CO, H_2 \) in blast gas, mol/s

\( n_{CO} \), \( n_{H2O} \): mole flow rates of \( N_2, CO, H_2 \) and \( H_2O \) in blast gas, mol/s

\( n_{CO} \), \( n_{H2O} \): mole flow rates of \( CO, H_2 \) and \( H_2O \) generated due to combustion, moisture decomposition, solution loss reactions and direct reduction, mol/s

\( n_{CO} \), \( n_{H2O} \): mole flow rates of \( CO, H_2 \) and \( H_2O \) generated due to indirect reduction, mol/s

\( n_1 \), \( n_2 \): mole flow rates of \( i \) gas \( (N_2, CO_2, CO, H_2 \) and \( H_2O \) produced in reactions 1 and 3, –

\( P \): blast pressure, Pa

\( Q_i \): heat loss from furnace per unit time, J/s

\( Q_i \): heat of combustion per unit mass of coal, J/kg

\( Q_{slag} \): sensible heat of slag per unit mass, J/kg

\( Q_{slag} \): heat of solution loss of coke, J/t-p

\( Q_C \): heat of combustion of coal and coke producing \( CO \) and \( H_2 \), J/t-p

\( Q_{coal} \): constant defined in Eq. (A-43), J/t-p

\( q_{C0} \): sensible heat of blast gas entering and leaving the furnace, J/t-p

\( q_{C0} \): sensible heat of blast gas entering the furnace, J/t-p

\( q_{G0} \): sensible heat of blast gas leaving the furnace, J/t-p

\( q_i \): heat loss from furnace, J/t-p

\( q_{pig} \): sensible heat of pig-iron per ton of pig-iron produced, J/t-p

\( q_{R} \): heat of reduction of \( Fe_2O_3 \) per ton of pig-iron produced, J/t-p

\( q_{slag} \): sensible heat of slag per ton of pig-iron produced, J/t-p

\( S_{C0} \): mass of slag produced from coke per unit ton of pig-iron produced, kg/t-p

\( S_{pig} \): mass of slag produced from iron ore per unit ton of pig-iron produced, kg/t-p

\( T_1 \): mean gas temperature in blowpipe-tuyere zone, K

\( T_{a0} \): ash fusion temperature, K

\( T_B \): initial blast gas temperature, K

\( T_{BL} \): blast gas temperature at blowpipe end, K

\( T_{C0} \): gas temperature at furnace exit, K

\( T_G \): blast gas temperature in blowpipe zone, K

\( T_{ig} \): ignition temperature, K

\( T_{ac} \): gas temperature at normal state (≈ 298 K), K

\( T_{pig} \): temperature of pig-iron, K

\( T_{F} \): theoretical flame temperature of bosh gas, K

\( T_i \): temperature of coal particle, K
Appendix A

Consumption of Coke and Reduction of Iron Ore within Blast Furnace

Coke carbon is consumed mainly by gasification, solution loss, direct reduction, inclusion in molten pig-iron and reductions of SiO₂ and MnO. The mass of coke carbon charged per ton of pig-iron produced, denoted as \( W_{\text{Cr}} \), is expressed as

\[
W_{\text{Cr}} = W_{Ct} + W_{Cs} + W_{Cd} + W_{Cp} + W_{Csi} \quad \text{(A-1)}
\]

where the subscripts \( Ct, Cs, Cd, Cp \) and \( Csi \) correspond to gasification, solution loss, direct reduction, inclusion in pig-iron and reductions of SiO₂ and MnO, respectively. This appendix deals with the derivations of \( W_{Ct}, W_{Cs}, W_{Cd}, W_{Cp} \) and \( W_{Csi} \) as well as the mass of pig-iron produced denoted as \( Fe = \text{final}/1000 \) with a unit of [t/s].

A-1 Properties of Gas Species Concerned in Blast Furnace

(1) Flows and Mole Rates of Gas Species

Figure 2 shows the flow diagram of gas species in a blast furnace. \( N_2, O_2 \) and \( H_2O \) gases enter the furnace from the tuyeres at the mole rates given by

\[
\begin{align*}
\dot{n}_{N_2} &= 0.79 \dot{V}_B / \dot{V}_{\text{MOL}} \quad \text{(A-2)} \\
\dot{n}_{O_2} &= \dot{V}_B \left[ \left( 0.21 / \dot{V}_{\text{MOL}} \right) + \left( \dot{m}_{O_2} / \dot{m}_{O_2} \right) \right] \quad \text{(A-3)} \\
\dot{n}_{H_2O} &= \dot{V}_B \dot{W}_{H_2O} / \dot{m}_{H_2O} \quad \text{(A-4)}
\end{align*}
\]

Including oxygen in the injected coal, the mole rate of oxygen supplied from the tuyeres denoted as \( \dot{n}_{O} \) is expressed as,

\[
\dot{n}_{O} = 2\dot{n}_{O_2} + \dot{n}_{H_2O} + \dot{m}_t \left( \dot{V}_B \dot{W}_F / \dot{m}_p \right) \quad \text{(A-5)}
\]

As this amount of oxygen is used for the overall gasification of coal and coke represented by reactions 3 and 5 in Table 1, \( n_O \) is also expressed as,

\[
\dot{n}_O = \left( W_{Ct} \dot{Fe} / \dot{m}_t \right) + \left( \dot{V}_B \dot{W}_F / \dot{m}_p \right) \quad \text{(A-6)}
\]

Next, in the bosh region, \( CO \) and \( H_2 \) gases are generated by reactions 3 and 5 and by reactions 3 and 8, respectively at the mole rates of \( n_{CO} \) and \( n_{H2} \) given by

\[
\begin{align*}
\dot{n}_{CO} &= \dot{n}_{O} \left( W_{Ct} \dot{Fe} / \dot{m}_t \right) + \left( \dot{V}_B \dot{W}_F / \dot{m}_p \right) \quad \text{(A-7)} \\
\dot{n}_{H2} &= \dot{V}_B \left[ \left( W_{H_2O} / \dot{m}_{H_2O} \right) + 0.5 \dot{m}_t \left( \dot{V}_B \dot{W}_F \dot{m}_p \right) \right] \quad \text{(A-8)}
\end{align*}
\]

\( CO \) and \( H_2 \) gases are also generated due to the solution
loss (reactions 6 and 7) and the direct reduction of iron ore (reaction 11). Then, the overall mole rates of CO and H₂ gases generated in the blast furnace, denoted as $n_{CO}$ and $n_{H_2}$, are obtained to be

$$n_{CO} = \left[ W_{CO} + (1 + \lambda_C) W_{C} + W_{Cd} \right] (Fe/m_c) + (V_B W_r/m_r)$$

$$n_{H_2} = n_{H_2} + (1 - \lambda_C) (W_{C} Fe/m_c)$$

where $\lambda_C$ is the mass fraction of the solution loss coke carbon consumed by CO₂.

Iron ore is reduced due to indirect and direct reductions while descending in the burden zone. As the reduction proceeds, the iron oxide changes its formula from Fe₂O₃ to FeO, FeO, FeO and Fe. The direct reduction as expressed by reaction 11 occurs for the molten wustite flowing on the coke surface (see the review of Muchi 19)). The indirect reductions are apparently represented by reactions 9 and 10.

The relation between $\eta_o$ and $\lambda_C$ is derived by substituting Eqs. (A-13)–(A-16) into Eqs. (A-24) and (A-25) and eliminating Fe with the aide of Eq. (A-24), the above equation is rewritten to be,

$$\sigma_C W_{CO} + \sigma_C W_{Cd} = (1 - \lambda_C) (m_e \sigma_C) M_o = J_2$$

(3) Mass Fraction of Solution Loss Coke Carbon Consumed by CO₂, $\lambda_C$

The reaction rate of the solution loss due to CO₂ (or H₂O) is assumed to be proportional to the mole concentration of CO₂ (or H₂O). Then, the mass fraction of the solution loss coke carbon consumed by CO₂, $\lambda_C$, is assumed by the mole ratio of CO₂ to the sum of CO₂ and H₂O gases generated, i.e.,

$$\lambda_C = n_{CO} \left/ \left( n_{CO} + n_{H_2O} \right) \right.$$  

Substitution of Eqs. (A-11) and (A-12) into Eq. (A-21) derives the following relation as,

$$\lambda_C = \lambda_{CO}$$

A-2 Coke Consumption Properties

Of $W_{Cp}$, $W_{Cd}$, $W_{C}$, $W_{Cd}$, and $W_{Cd}$ appeared in Eq. (A-1), the values of $W_{Cp}$ and $W_{Cd}$ are assumed by empirically obtained ones. That is, the contents of [C] = 4.59%, [Si] = 0.58% and [Mn] = 0.76% in molten pig-iron reported by Yagi et al. are referred, resulting in the value of $(W_{Cp} + W_{Cd})$ being equal to 53 kg/t-p.

For $W_{Cd}$, using $\lambda_{Cd}$,

$$W_{Cd}/m_c = \lambda_{Cd} M_o$$

(2) CO and H₂ Gases Utilized for Iron Ore Reduction

The reduction abilities of CO and H₂ gases are represented by $\sigma_{co}$ and $\sigma_{H_2}$ in Eqs. (A-11) and (A-12). Conventionally, the overall fractions of CO and H₂ gases utilized for iron ore reduction defined as follows are used:

$$n_{CO} = n_{CO} (1 - \sigma_{co})$$

$$n_{CO} = n_{CO} (1 - \sigma_{co})$$

The relation between $\eta_o$ and $\sigma_{co}$ and that between $\eta_{H_2}$ and $\sigma_{H_2}$ are derived by substituting Eqs. (A-13)–(A-16) into Eqs. (A-17) and (A-18), respectively. The resultant formulae are

$$\frac{\sigma_{co} - \eta_{co}}{1 - \eta_{co}} = \frac{\lambda_C (W_{C} Fe/m_c)}{n_{CO}}$$

$$\frac{\sigma_{H_2} - \eta_{H_2}}{1 - \eta_{H_2}} = \frac{(1 - \lambda_C) (W_{C} Fe/m_c)}{n_{H_2}}$$

The above equations indicate that $\sigma_{co}$ (or $\sigma_{H_2}$) must be greater than $\eta_{co}$ (or $\eta_{H_2}$).
A-3 Heat Balance of Blast Furnace

The following heats denoted by \( q \) with a unit of J/t-\( p \) are taken into account, i.e.,
\[
q_C + q_{Ct} + q_{C0} - q_L - q_{pig} - q_{slag} = 0 \quad \ldots (A-27)
\]
where \( q_C \) is the heat of gasification of coal and coke, \( q_{Ct} \) is the heat of solution loss, \( q_{C0} \) is the heat of reduction of iron ore, \( q_L \) is the sensible heat of the blast gas entering and leaving the furnance, \( q_{pig} \) is the heat loss from the furnace wall and \( q_{slag} \) are the sensible heats of pig-iron and slag produced from the furnace.

(1) Heat of Gasification, \( q_C \)

Let the heats of reactions 3 and 6 be \((-\Delta H_3)\) and \((-\Delta H_6)\) corresponding to the overall gasification reactions of coal and coke,
\[
q_C = \left[ (-\Delta H_1) (V_B W_F / m_F) / Fe \right] + (-\Delta H_6) (W_{Ct} / m_{Ct}) = J \cdot W_{Ct} \quad \ldots (A-28)
\]
where \( J = \left[ (-\Delta H_1) (V_B / m_F) / J_i \right] + (-\Delta H_6 / m_{Ct}) \).

(2) Heat of Solution Loss of Coke, \( q_{Ct} \)

Let the heats of reactions 5 and 7 be \((-\Delta H_5)\) and \((-\Delta H_7)\),
\[
q_{Ct} = \left[ (-\Delta H_5) \lambda_{Ct} + (-\Delta H_7) \left( 1 - \lambda_{Ct} \right) \right] (W_{Ct} / m_{Ct}) = J \cdot W_{Ct} \quad \ldots (A-29)
\]
where \( J = \left[ (-\Delta H_5) \lambda_{Ct} + (-\Delta H_7) \left( 1 - \lambda_{Ct} \right) \right] / m_{Ct} \).

(3) Heat of Reduction of Iron Oxide, \( q_R \)

The moles of oxygen given by \( \lambda_{Di} \) of the charged iron ore oxygen is removed directly by reaction 11 with the heat of \((-\Delta H_{11})\). The indirect reduction occurs simultaneously for the remaining oxygen given by \((1-\lambda_{Di})M_{Di} \). Then, \( q_R \) is obtained as
\[
q_R = \left\{ \left[ (-\Delta H_{11}) \lambda_{Di} + (-\Delta H_5) \lambda_{CO} + (-\Delta H_{10}) (1-\lambda_{CO}) \right] \right\} \left( 1 - \lambda_{Di} \right) M_{Di} \quad \ldots (A-30)
\]
where \((-\Delta H_5)\) and \((-\Delta H_{10})\) are the heats of reactions 9 and 10 (indirect reduction).

(4) Sensible Heat of Blast Gas Entering and Leaving the Furnace, \( q_{Gas} \)

The sensible heat of the blast gas entering the furnace \( q_{Gas} \) is given by
\[
Fe \cdot q_{Gas} = \int_T^{T_1} \left\{ \sum n_i C_p \right\} dT = V_B \int_T^{T_1} \left\{ \sum n_i / V_B \right\} C_p dT \quad \ldots (A-31)
\]
where the subscript \( i \) corresponds to \( N_2, O_2 \) and \( H_2O \) whose mole rates are already given by Eqs. (A-2)–(A-4).

Next, the gas species of \( N_2, CO, CO_2, H_2 \) and \( H_2O \) leave the furnace exit at the mole rates given by Eqs. (A-13)–(A-16). The sensible heat of the gases \( q_{Gas} \) is expressed by
\[
Fe \cdot q_{Gas} = \int_T^{T_1} \left\{ \sum n_i C_p \right\} dT = V_B \int_T^{T_1} \left\{ \sum n_i / V_B \right\} C_p dT \quad \ldots (A-32)
\]
where
\[
q_{Gas} = \int_T^{T_1} \left\{ \sum n_i C_p \right\} dT
\]

(5) Heat Loss from Furnace Wall, \( q_L \)

The heat loss from the furnace wall, \( q_L \) is expressed as
\[
q_L = Q_L / Fe \quad \ldots \ldots \ldots (A-34)
\]
where \( Q_L \) has a unit of J/s. Using \( Q_L, Fe \) and \( q_L \), the values under a standard state condition, and assuming that \( Q_L \) is constant, \( i.e., \ Q_L = Q_L^0 \), the above equation is
\[
q_L = Q_L^0 \cdot Fe^\epsilon \quad \ldots \ldots \ldots \ldots (A-35)
\]

(6) Sensible Heat of Pig-iron Produced, \( q_{pig} \)

The value of \( q_{pig} \) is dependent of the pig-iron temperature, \( T_{pig} \). The following simplification is adopted, \( i.e., T_{pig} \) is assumed to be constant, \( i.e., T_{pig} = T_R \).

\[
q_{pig} = \int_{T_R}^{T_pig} \left( 1000 C_p \right) dT \propto \left( T_{pig} - T_R \right) \quad \ldots (A-36)
\]

Further, \( T_{pig} \) is assumed to be proportional to \( T_R \), the adiabatic flame temperature of the bosh gas, \( i.e., T_{pig} / T_R = T_{pig} / T_R \).

The above equation is rewritten to be
\[
q_{pig} = \frac{T_{pig} - T_R}{T_{pig} / T_R} q_{pig}^0 = \frac{T_{pig} - T_R}{T_{pig} / T_R} q_{pig}^0 \quad \ldots (A-37)
\]

(7) Sensible Heat of Slag Produced, \( q_{slag} \)

The sensible heat of slag is given by
\[
q_{slag} = \left( S_{1C} + S_{1Fe} \right) Q_{slag} \quad \ldots (A-38)
\]
where \( Q_{slag} \) is the sensible heat of slag per unit mass and \( S_{1C} \),
and $S_{CS}$ and $S_{Fe}$ are the masses of coke slag and iron ore slag, respectively per unit ton of pig-iron produced, i.e.,

$$S_{LC} = \left[ f_{CS} / (1 - f_{CS}) \right] \left[ W_{CS} + W_{CS} + W_{CS} + W_{Fe} \right]$$

$$S_{Fe} = \left[ f_{FeS} / (1 - f_{FeS}) \right] \left[ W_{FeS} + W_{FeS} + W_{FeS} + W_{FeS} \right]$$

(A-39)

(A-40)

where $f_{CS}$ and $f_{FeS}$ are the mass fraction of slag in coke and that in iron ore, respectively. Then, Eq. (A-38) is rewritten as

$$q_{slag} = J_7 \left( W_{CS} + W_{FeS} \right) + q_{FeS}$$

(A-41)

where

$$J_7 = \left[ f_{CS} / (1 - f_{CS}) \right] Q_{slag}$$

$$J_{qc} = S_{FeS} Q_{slag} + J_7 \left( W_{CS} + W_{FeS} + W_{FeS} \right)$$

Likewise $q_{FeS}$ given by Eq. (A-37), $Q_{slag}$ is dependent of the slag temperature and the following equation is adopted,

$$Q_{slag} = T_{pig} \left( T_r / T_r \right) - T_{pig}$$

$$T_{pig} - T_{pig} \ Q_{slag}$$

(A-42)

where the temperature of pig-iron and that of slag are assumed to be the same.

(8) Final Form of the Heat Balance Equation

Equation (A-27) is rewritten by substituting Eq. (A-28) into $q_C$, Eq. (A-29) into $q_{Cs}$, Eq. (A-33) into $q_{Fe}$, Eq. (A-35) into $q_L$ and Eq. (A-41) into $q_{slag}$ as

$$J_8 W_{CS} + J_9 W_{Fe} = q_{const}$$

(A-43)

where

$$J_8 = J_9 + J_9 - J_9 - J_9$$

$$J_9 = J_9 - J_9 - J_9$$

$$q_{const} = - q_{pig} + J_9 W_{FeS} + q_{pig} + J_9$$

A-4 Calculations of $W_{CS}$, $W_{CS}$ and $Fe$

For three variables $W_{CS}$, $W_{CS}$ and $Fe$, three independent equations have been derived, i.e., Eqs. (A-24), (A-26) and (A-43). $W_{CS}$ and $W_{CS}$ are obtained by solving simultaneously the two equations, Eqs. (A-26) and (A-43) as they do not include $Fe$.

$$W_{CS} = \sigma_{CS} q_{const} - J_9 J_9$$

$$W_{CS} = \sigma_{CS} J_9 - \sigma_{CS} J_9$$

(A-44)

(A-45)

The value of $Fe$ is evaluated by substituting thus obtained $W_{CS}$ into Eq. (A-24).