Effect of Coke Diameter and Oxygen Concentration of Blast on Cupola Operation

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Because the cupola does not require a reducing agent, CO₂ generation can be greatly reduced in comparison with the blast furnace process. Moreover, because the latent heat of the cupola off-gas can be utilized effectively in steel plants by blast furnace gas recovery equipment, the cupola was introduced in JFE Steel East Japan Works. In this report, the effects of coke diameter and oxygen concentration of blast on the reaction rates of coke combustion, coke gasification and carburization in the cupola were studied. Operation was simulated from the viewpoints of these reactions and heat transfer between coke/scrap and shaft gas. In addition, the changes in the off-gas composition, coke rate, hot metal composition, were observed in an operating small cupola under several conditions of coke diameter and oxygen concentration of blast.

KEY WORDS: cupola; coke rate; oxygen concentrations of blast; solution loss; carburization; simulation; shaft furnace.

1. Introduction

Reduction of CO₂ emissions is the most important purpose of iron making research. Processes, which satisfy both environmental protection and cost efficiency are also demanded in the steel industry. Innovative processes such as COURSE50 (CO₂ Ultimate Reduction in Steel making process by innovative technology for cool Earth 50) are currently developed.

Utilization of scrap, which already exists in the market, is an effective measure for reducing CO₂. The cupola can produce molten pig iron from cold iron or steel. In the cupola process, scrap, cast pig iron, and similar materials are used as raw materials, and foundry coke (large lump/low reactivity coke) is used as the heat source.¹ ⁶ Due to the simplicity of this process, it is used in small and medium-scale casting shops. Because the cupola does not require a reducing agent, CO₂ generation can be greatly reduced in comparison with the blast furnace process. Moreover, because the latent heat of the off-gas can be used effectively, cupolas have been introduced in integrated steel works.⁶

In integrated steel works, a larger-scale cupola is constructed to secure a large amount of hot iron. Blast furnace coke (metallurgical coke), which is smaller in diameter than foundry coke, and oxygen, which is produced for decarburization of iron, are also actively utilized in cupola operation.

Therefore, in the present research, the effect of changes in the coke diameter and the oxygen concentration of blast on cupola operation was studied, considering the combustion and gasification reactions from the viewpoint of reaction rate theory. Operation was also performed with a high charging rate of small diameter coke and high oxygen concentration. The changes in the off-gas composition, coke rate, hot metal composition, etc. were observed.

2. Outline of Cupula

2.1. Outline of Cupula Process

Figure 1 shows a schematic diagram of the cupula. Normally, a cupula has a furnace height of 6–8 m and a furnace diameter of 2–4 m, and has a production capacity of 500–2,000 t/d. Scrap/coke are charged from the furnace top, and the traveling time in the furnace is 30–40 min. Operation is
normally performed with a 1-stage tuyere, but in some rare cases, secondary combustion (post-combustion) is actively performed using a multi-stage tuyere system. Air is generally supplied as hot blast with a temperature of around 600°C. Oxygen enrichment is performed during periods of increased production. Raw materials are charged by a charging tube method, and leakage of CO from the furnace top is prevented by suction of the off-gas. A siphon method is employed for continuous tapping of melted iron and slag.

Various types of scrap are used. H2, which is a representative type of scrap, has a length of 1.2 m or less and thickness of 6 mm or less. Pig iron-type raw materials such as cast pig iron are also used. “Foundry coke” has a diameter approaching 200 mm and low reactivity. In some cases, blast furnace coke screened to a size of 60 mm or larger is also used.

The general operating parameters of the cupola are shown in Table 1. In comparison with the blast furnace, the tapping temperature is the same or somewhat higher, and the carbon concentration of the tapped hot metal is approximately 1% lower. The coke rate (130 kg/t) and slag ratio (approx. 50 kg/t) are both much lower. The unit values for blast and off-gas are approximately half those of the blast furnace. The gas utilization ratio is on the order of 40%, and the off-gas temperature is approximately 250°C.

2.2. Reactions in Cupula

In the cupula, combustion of coke occurs directly in front of the tuyere, and the scrap is melted by heat exchange with the high temperature gas generated by combustion of the coke. The important phenomena in the furnace are (1) the coke combustion reaction, (2) the coke gasification reaction, (3) gas-scrap heat exchange and (4) the scrap carburizing reaction.

2.2.1. Coke Combustion Reaction

The carbon contained in the coke is oxidized to carbon dioxide by the oxygen introduced into the furnace from the tuyere. Various mechanisms of coke combustion by oxygen gas have been proposed. However, a reaction rate equation (Eq. 1), which considers boundary film resistance and the chemical reaction, was used in the present research.

\[
R_c = \frac{6(1-\varepsilon)}{D_p \Phi} \left( \frac{1}{k_f + 1/\Phi} \right) \frac{T}{P_{O_2}} \frac{12}{1273} \left( \frac{1}{R_T} \right)
\]

\[
k_f = \frac{Sh \cdot D_{O_2} / D_p}{1 + 1/\Phi}
\]

\[
Sh = 2.0 + 0.55 \left( \frac{Re}{Sc} \right)^{1/2}
\]

\[
k_c = 3.78 \times 10^{-7} \exp(-45000 / RT)
\]

Figures 2 and 3 show the relationship between temperature and coke diameter and the coke combustion reaction rate obtained from (Eq. 1). Because the combustion temperature of coke normally reaches a high temperature exceeding 2000°C, it is considered that the boundary film resistance, and not the chemical reaction, is the rate-controlling process. At a temperature of 1700°C, the reaction rate is inversely proportional to the 1.5 power of the coke diameter. Thus, it can be understood that the coke diameter has a large effect on the reaction rate at this temperature.

2.2.2. Coke Gasification Reaction

The gasification reaction of coke is also called a solution loss reaction, and occurs after substantially all oxygen has disappeared. It is known that this gasification reaction is an endothermic reaction, which removes heat from the hot shaft gas and the shaft gas volume is increased. Numerous

| Table 1. Representative operating conditions. |
|---------------------------------------------|
| Productivity | 6.9 kg/s |
| Tapping temperature | 1530°C |
| Tap C | 3.70% |
| Slag ratio | 49 kg/t-pig |
| Coke rate | 129 kg/t-pig |
| Charge iron rate | 10% |
| Coke diameter (BF) | 56 mm |
| Coke diameter (Foundry) | 160 mm |
| Blast consumption | 565 Nm³/t-pig |
| O₂ consumption | 5.5 Nm³/t-pig |
| Blast temperature | 550°C |
| Gas utilization ratio | 41% |
| Off-gas temperature | 250°C |
| Off-gas flow rate | 634 Nm³/t-pig |
| Heat loss | 600 MJ/t-pig |
researches on the solution loss reaction of coke in the blast furnace also exist. It is necessary to study the reaction at a comparatively high temperature. In the present research, boundary film resistance and the chemical reaction were considered.

\[ R_s = \frac{6(1-\varepsilon)}{D_p \cdot \Phi (1/k_{f} + 6/D_p E_{k_s})} \cdot \frac{T}{273} \cdot \frac{P_{CO_2}}{101300} \cdot 22.4(1-C_{ash}) \]

\[ k_f = Sh \cdot D_{CO_2} / D_p \]

\[ Sh = 2.0 + 0.55 (Re)^{0.5} (Sc)^{0.25} \]

\[ k_s = 2.99 \times 10^3 \exp(-80000 / RT) \]

Figure 4 and 5 show the relationship between temperature and coke diameter and the coke gasification reaction rate obtained from (Eq. 2). These results suggest that the gasification reaction rate is controlled by the reaction rate and boundary film resistance at around 1 500°C, at which it actually occurs. As the reaction rate is inversely proportional to the 1–1.5 power of the coke diameter, it can be understood that the coke diameter has a large effect on the reaction rate.

2.2.3. Gas-scrap Heat Exchange

Gas-scrap heat exchange occurs by counterflow. The basic equation of convective heat exchange is shown by (Eq. 3). Thus, an analytical solution can be obtained. \( \beta \) is inversely proportional to the 1.5 power of the scrap diameter and inversely proportional to the 0.5 power of the gas flow velocity. The furnace temperature (distribution) is changed by the function of \( \alpha \) and \( \beta \). According to this analysis, the furnace temperature distribution is a function of the heat flux ratio (\( \alpha \)) and the heat exchange coefficient (\( \beta \)).

\[ \frac{C_{pg} G_s}{C_{pg} G_s} \frac{dT}{dz} + H(T_s - T_g) = 0 \]

\[ \frac{C_{pg} G_s}{C_{pg} G_s} \frac{dT}{dz} + H(T_s - T_g) = 0 \]

\[ \alpha = \frac{C_{pg} G_s}{C_{pg} G_s} \beta = \frac{LH}{C_{pg} G_s} \]

\[ H = 6(1-\varepsilon) \cdot \frac{k_s}{Dp \cdot \Phi} \cdot \frac{T}{Dp} \cdot 2.0 + 0.6(\frac{G \cdot Dp}{\mu})^{0.5} \cdot 12^{1.5} \]

Figure 6 shows the relationships among heat transfer efficiency and the heat flux ratio (\( \alpha \)) and heat exchange coefficient (\( \beta \)) for a system in which heat loss does not occur. Here, heat transfer efficiency is expressed by (Eq. 4). When calculated using ordinary values for \( \alpha \) and \( \beta \), the thermal efficiency in normal operation exceeds 90%. Heat transfer efficiency (scrap heating efficiency) can be improved by various techniques, such as reducing the scrap thickness, etc.

Heat transfer efficiency = \( \frac{Q_{s}}{Q_{g} + Q_{s}} \) \hspace{1cm} (4)

An example of the heat flux ratio in an actual cupola is shown in Table 2. As shown in this table, the heat flux ratio in the cupola did not exceed 1. To estimate the actual temperature distribution in a cupola, it is also necessary to correct for heat loss. Here, the corrected heat flux ratio shown in (Eq. 5) was used for simplicity. The heat loss of this cupola is 400 MJ/t-iron. Because the corrected heat flux ratio becomes 20% bigger (\( \alpha' > 1 \)), it is considered that the cupola temperature curve has a concave shaped bottom.

\[ \alpha' = \frac{AC_{ps} Gs + Q / Ts(0)}{AC_{pg} Gg} \]

2.2.4. Scrap Carburizing Reaction

When scrap is carburized, the melting point of the metal is reduced. The temperature of the molten metal is increased slightly after dripping, because the heat exchange time of the droplets and gas is reduced. The dripping start temper-
Temperature has a large effect on the tapping temperature.

Carburizing reactions comprise solid carburizing and gas carburizing. Figure 7 shows the change in the CO/CO₂ temperature in the cupola. Because the oxygen potential in the cupola is high in comparison with that in the blast furnace, the carburizing reaction in the cupola is considered to occur by direct contact with the coke. Therefore, a simulation of the carburizing reaction of scrap was attempted. Assuming the shape of the scrap is a round bar with a diameter of 20 mm, coke was assumed to be in contact with 20% of the circumference of this shape. It was also assumed that the carbon is diffused in a solid state, and after reaching the melting point, it is transferred by flow at 0.1 m/s. For temperature, the furnace temperature distribution obtained in a previous simulation (increase from room temperature to 1500°C in approximately 30 min) was assumed.

Figure 8 shows the carbon concentration distribution in the round bar at each temperature. According to this figure, if the temperature does not reach at least 1450°C, carbon is not transferred to the whole bar. As a result, the scrap does not reach the melting point, and melting and dripping of molten scrap do not occur. From this simulation, it was concluded that the molten scrap is carburized to the saturation carbon concentration. However, in actual cupolas, carburization is limited to a carbon concentration of approximately 3.5–4%. Although, this phenomenon is inexplicable, there is a possibility that the carburization reaction is reduced due to the high oxygen potential in the furnace or/and the presence of ash on the contact surface, which suppresses carburization.

### 2.3. Case Study of 1-Dimensional Simulation Model

#### 2.3.1. Method of 1-Dimensional Simulation Model

In the cupola, the various reaction and heat exchange processes must be considered. The simplest 1-dimensional steady state cupola model was prepared, and the effects of the coke diameter and oxygen concentration of blast on operation were studied.

This model was created so as to treat the coke phase, scrap phase, and gas phase. In heat exchanges between these phases, only gas-solid transfer was considered, and solid-solid transfer was ignored. Among the reactions in the furnace, the coke combustion reaction (Eq. 1) and solution loss reaction (Eq. 2) were treated by reaction rate theory. At this time, the change in coke diameter due to the reactions was considered. The carburizing region was defined as from 1350°C to 1450°C, and within this region, linear change of the carbon concentration from 0% to 3.7% was assumed.

### 2.3.2. Results of Prediction by Simulation Model

(1) Simulation results of furnace temperature and gas composition distribution

Figure 9 shows the simulation results of the furnace temperature and gas composition distribution. It can be understood that the O₂ concentration remains up to a fairly high temperature.
position in the furnace, and disappears at the highest point of CO\textsubscript{2} concentration. This is attributed to the large diameter and low reactivity of the coke in comparison with the blast furnace.

It can be understood that the CO concentration also rises simultaneously with the disappearance of O\textsubscript{2}, becoming constant in the region higher than approximately 2.5 m, and the solution loss reaction occurs in this region. The temperature of the solution loss reaction is from 1500°C to 2200°C. Thus, this temperature is higher than that in the blast furnace.

CO gas is not utilized for reduction, as it is in the blast furnace, because a raw material containing reducible oxygen, such as DRI, is not charged. An off-gas, which contains a large amount of latent heat is released from this furnace.

Above the solution loss reaction region, around approximately 1.8 m, the temperature of the scrap exceeds 1450°C, and melting and dripping occur. Solid scrap does not exist below this level, and the lower part of the furnace becomes a packed bed consisting of only coke. Therefore, substantially the entire solution loss reaction occurs in this region.

(2) Effect of oxygen concentration of blast and coke diameter on operation

Using this model, the effects of the oxygen concentration of blast and coke diameter on the operation were studied. Here, the blast rate and oxygen concentration were set so as to obtain a constant off-gas volume, and the coke rate was adjusted to maintain a constant hot metal temperature. Two cases were studied, in which the ratio of small diameter coke was set at 50% or 100%, while changing the oxygen concentration of blast in the range from 21% to 50%.

Figures 10–12 show the oxygen concentration dependency of changes in the furnace top temperature, coke rate, and CO\textsubscript{2}/(CO+CO\textsubscript{2}), respectively. The furnace top temperature decreases due to the increasing heat flow ratio, and the solution loss region, where the temperature is high and only coke, and no scrap exists, also becomes smaller, thereby increasing CO\textsubscript{2}/(CO+CO\textsubscript{2}).

On the other hand, when oxygen concentration is increased to more than 40%, the solution loss region also becomes smaller. However, the temperature of the solution loss region becomes excessively high, and this is considered to cause activation of the solution loss reaction. As a result, the CO\textsubscript{2}/(CO+CO\textsubscript{2}) deteriorates.

It can also be understood that the gas utilization ratio and coke rate deteriorates as the coke diameter becomes smaller, because the solution loss reaction occurs more easily.
3. Actual Cupola Test of Effect of Changes in Coke Diameter and Oxygen Concentration of Blast

3.1. Test Method

Operation using a high ratio of small diameter coke and high oxygen concentration of blast was performed in an operating small-scale cupola. The Table 3 shows the specification of cupola, which is used for this experiment. The two types of coke used were large lump coke with a harmonic mean diameter of 192 mm and small diameter coke with diameter of 57 mm. Operation was performed with the blending ratio of the small diameter coke changed in the range from 40% to 100%. As iron sources (cast pig iron, return scrap, steel scrap, etc.) were used. The blending ratio of pig iron-type raw materials was 35%. In addition to the above materials, lime and ferrosilicon were also used. Tables 4–6 show the diameter of the coke, the diameter and composition of the lime, and the diameter and composition of the ferrosilicon, respectively. An experiment was also performed with oxygen concentration increased to a maximum concentration of 36%.

As suggested by the model, in actual operation, there were large changes in the temperature of the hot metal when operation conditions were changed. In this experiment, the coke rate and other operating conditions were adjusted so as to maintain a virtually constant tapping speed, hot metal temperature, and carbon concentration of iron. Operation was continued for a sufficiently long period, which could be regarded as the steady state, and the average coke rate, furnace top gas composition, heat loss, etc. were observed.

3.2. Effect of Oxygen Concentration of Blast on Cupola Operation

The relationship of oxygen concentration of blast and heat loss is shown in Fig. 13. The relationship of oxygen concentration and heat transfer efficiency is shown Fig. 14. Heat loss decreases and heat transfer efficiency increases as oxygen concentration increases. When the oxygen concentration is increased, the heat flux ratio inevitably increases, and the scrap melting position moves to a lower level in the furnace. Provided an eccentric gas flow (channeling) or other abnormal phenomenon does not occur, it is considered that heat transfer efficiency will increase and the furnace top temperature will decrease.

The relationship between the concentration and gas utilization ratio is shown in Fig. 15. According to the operational results, gas utilization can be improved by increasing the oxygen concentration of blast. The cause of this phenomenon is considered to be the same as in simulation results.

According to the operational results, gas utilization can be improved by increasing the oxygen concentration. The cause of this phenomenon is considered to be the same as in simulation results.

3.3. Effect of Coke Diameter on Cupola Operation

The relationship between the small diameter coke blending ratio and the coke rate is shown in Fig. 16. It can be understood that the coke rate increases as the amount of small diameter coke blending is increased. In this operation, the tapping temperature did not change greatly, and there was virtually no change in heat loss or heat transfer efficien-

| Table 3. The specification of cupola for the experiment. |
|----------------------------------------------------------|
| Furnace diameter | 2.1 m |
| Tuyere number | 6 |
| Tuyere diameter | 0.14 m |
| Melting Capacity | 20–25 t/H |

| Table 4. Property of BF coke and fondly coke. |
|---------------------------------------------|
| Blast furnace coke (Harmonic mean diameter) | Coke ash |
| particle diameter (small) | 57 mm | 12% |
| Foundry coke (large) | 192 mm | 10% |

| Table 5. Particle diameter and composition of lime. |
|----------------------------------------------------|
| Diameter (mm) | CaO (%) | SiO₂ (%) | Al₂O₃ (%) | MgO (%) | Fe₂O₃ (%) |
| 30–60 | 55.6 | 0.16 | 0.05 | 0.53 | 0.05 |

| Table 6. Particle diameter and composition of ferrosilicon. |
|-------------------------------------------------------------|
| Diameter (mm) | Si (%) | Al (%) | P (%) | S (%) | C (%) |
| 30–60 | 76.4 | 1.34 | 0.019 | 0.0003 | 0.082 |

Fig. 13. Effect of oxygen concentration on heat loss.

Fig. 14. Effect of oxygen concentration on heat transfer efficiency.
The relationship between the change in the coke rate and the gas utilization ratio is shown in Fig. 17.

It can be understood that gas utilization ratio decreases in the case of a high coke rate. It is considered that the use of small diameter coke, which has a larger specific area, increased the solution loss reaction. Because this reaction is endothermic, some other heat source must be supplied and it is considered that this led to an increase in the coke rate.

4. Conclusions

In order to investigate the effect of coke diameter and oxygen concentration of blast on cupola operation, a 1-dimensional steady state cupola model was made. Experimental operation was also performed with a small-scale cupola by varying the small diameter coke rate and the oxygen concentration of blast.

The following conclusions were obtained.

(1) Increasing the oxygen concentration of blast reduces heat loss and the coke rate and increases thermal efficiency. The high temperature region in the furnace is reduced due to the increased heat flux ratio accompanying oxygen concentration, and the time available for the solution loss reaction is shortened due to the smaller high temperature region.

(2) Increasing the blending ratio of small diameter coke decreases the gas utilization ratio and increases the coke rate. These change are attributed to the increase in solution loss reaction due to the increased specific area of the coke when smaller diameter coke is used.

\[
\begin{align*}
R_C &: \text{Combustion reaction rate (kg-coke/m}^3\text{s)} \\
R_G &: \text{Gasification reaction rate (kg-coke/m}^3\text{s)} \\
D_p &: \text{Coke diameter (m)} \\
\Phi &: \text{Shape factor (–)} \\
k_f &: \text{Boundary film resistance factor (m/s)} \\
k_c &: \text{Combustion reaction factor (m/s)} \\
k_g &: \text{Gasification reaction factor (m/s)} \\
E_f &: \text{Effective gasification reaction coefficient (–)} \\
P_{CO_2} &: \text{Partial pressure of CO}_2 (\text{kg/m}^2\text{s}) \\
P_{O_2} &: \text{Partial pressure of O}_2 (\text{kg/m}^2\text{s}) \\
Q_{m} &: \text{Sensible heat of molten iron slag} \\
Q_{e} &: \text{Sensible heat of off-gas} \\
A &: \text{Area of cross section of cupula (m}^2\text{)} \\
C_{pm} &: \text{Heat capacity of sold matters (kJ/kg}^\circ\text{C)} \\
C_{pg} &: \text{Heat capacity of gases (kJ/kg}^\circ\text{C)} \\
G_s &: \text{Mass flow of solid matters (kg/m}^2\text{s)} \\
G_g &: \text{Mass flow of gases (kg/m}^2\text{s)} \\
T_s &: \text{Solid matter temperature (}^\circ\text{C)} \\
T_g &: \text{Gas temperature (}^\circ\text{C)} \\
H &: \text{Heat transfer coefficient (kJ/s}^\circ\text{C)} \\
L &: \text{Furnace hight (m)} \\
\varepsilon &: \text{Porosity ratio (–)} \\
\mu &: \text{Viscosity coefficient (kg/m}\cdot\text{s)} \\
Pr &: \text{Prandtl Number (–)} \\
Q &: \text{Heat loss of cupula (kJ/s)} \\
\alpha &: \text{Heat flux ratio (–)} \\
\beta &: \text{Heat exchange coeffient(–)}
\end{align*}
\]

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