KAWASAKI STEEL TECHNICAL REPORT
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1 Introduction

Si content in pig iron has long been used as one of the indices to represent the thermal state of the high temperature region at the lower region of the blast furnace, mainly the dropping zone[1,2]. Moreover, in recent years, the control of Si content in pig iron, particularly at the lower level of concentration such as 0.1–0.3%, has been regarded as one of operational problems, due to the following reasons. In the converter steel making process, technological development has been pursued with regard to slagless or slag minimum refining[3-8] which requires the supply of low-Si pig iron. While low-Si pig iron can be made without using the blast furnace by desiliconizing pig iron with oxidizing agents such as iron oxide[3,6,9], the desiliconization treatment outisde the blast furnace requires additional investment, increased running cost as well as cost for disposing slag. It is desirable, therefore, to produce low-Si pig iron in the blast furnace because the process does not require additional facilities in particular.

On the other hand, the production of low-Si pig iron in the blast furnace presents an operational disadvantage as it lowers thermal level at the furnace bottom, or in other words, the dropping zone level. Especially when Si content as low as 0.1–0.2% is desired, the hot metal temperature is sometimes markedly lowered. In the case of insufficient discharging of hot metal or slag or a large slipping in the lower part of the furnace, a serious accident such as hearth chilling may be induced. Accordingly, the production of low-Si pig iron requires stable operation which ensures a smooth and regular burden descent, and an unstable operation that may result from the smelting of low-Si pig iron itself must be avoided. Other important operational requirements involve provision of adequate hearth volume through sufficient discharge of hot metal and slag, and proper hearth temperature control. At present, no technology has yet been established to produce 0.1–0.2% Si pig iron without any operational risk. The present report concerns the principle of low-Si iron smelting based on the operational data of our blast furnaces and some of the technical problems to be solved in the future.

2 Changes of Si Content in Pig Iron

In the past decade, Si content in pig iron and fuel rate changed, as shown in **Fig. 1**. Two oil crises, one in 1973 and the other 1978, triggered a deterioration in coke quality and seriously affected the operation of blast furnaces. Nevertheless, it is evident that Si content and fuel rate decreased continuingly as a general trend. Ignoring details, this trend may be said to reflect the following technical background. That is, considering no marked rise in blast furnace productivity over the decade, factors contributing to the lowering of fuel rate are the rise in blast temperature,

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** Research Laboratories

*** Chiba Works

**** Mizushima Works

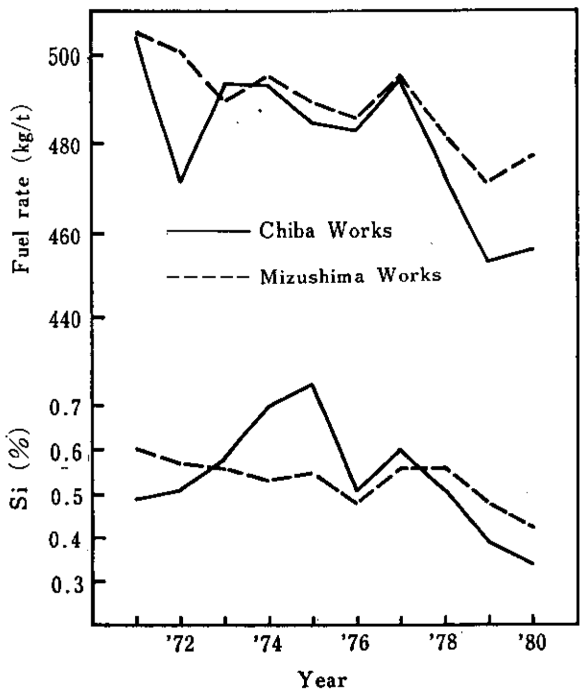

Fig. 1 Change of Si content in pig iron and fuel rate during the last decade at Chiba and Mizushima Works

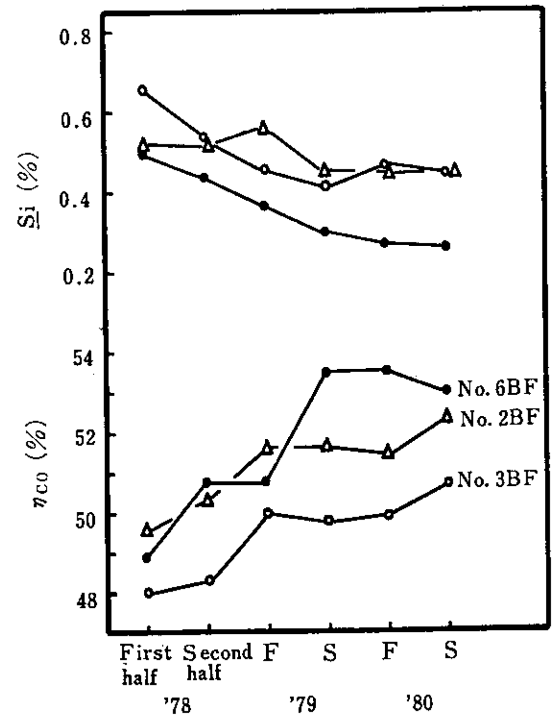

Fig. 2 Half-yearly change of CO gas utilization and its contribution to Si content in pig iron at Chiba Works

reduction in heat loss from the furnace wall, and improvement in utilization of furnace top CO gas. The correlation of reduced fuel rate to lowered Si content in pig iron may be attributed, in general, to the reduction in SiO sources per ton of pig iron due to reduced fuel rate, and to the lowering of dropping zone due to improved reducibility of burden ores and improved gas utilization based on an optimized burden distribution at the furnace top. Generally, an improved top gas utilization leads to an ample accumulation of heat at the lower part of the furnace, raising the hot metal temperature and the Si content. In such a case, it is customary to turn to an operational mode of elevating the thermal flow ratio by increasing the ore/coke ratio. The temperature distribution in a furnace with higher thermal flow ratio is characterized by the down-ward shift of thermal reserve zone, that is, the lower height of dropping zone (see **Fig. 8**). The relationship of this feature to the Si content can be explained by the method of smelting low-Si pig iron, described below. Above all, the effort to lower the fuel rate through the improvement of gas utilization greatly contributed to the consequent lowering of Si content in pig iron, as shown in **Fig. 2**. This factor is important in respect of the previous background of operational technology.

3 Method of Smelting Low-Si Pig Iron

Silicon is dissolved into pig iron mainly by the following process[10]: as pig iron including carbon drops through void spaces in the coke-packed bed corresponding to the dropping zone, SiO contained in the bosh gas which rises through the same spaces is reduced by carbon in the pig iron. The chemical reaction is represented by equation **(1)**.

$$\mathrm{SiO\,(gas)} + \underline{\mathrm{C}} \longrightarrow \underline{\mathrm{Si}} + \mathrm{CO\,(gas)} \quad \cdots\cdots\mathbf{(1)}$$

If pig iron is saturated with carbon, the rate equation for reaction **(1)** is given by **(2)**[11]. It is assumed that if the Si content in pig iron is lower than 1%, the contribution by the backward reaction is negligible.

$$\frac{\rho_M \cdot H_M}{m_{Si} \cdot A_{GM}} \frac{d[\%Si]}{100dt} = k_f \cdot P_{SiO} - k_b \cdot P_{CO} \cdot a_{Si} \doteqdot k_f \cdot P_{SiO} \quad \cdots\cdots\cdots\mathbf{(2)}$$

k_f and k_b: Apparent rate constants of forward and backward reactions, respectively
ρ_M and H_M: Density and total hold-up of pig iron
m_{Si}: Molecular weight of silicon
A_{GM}: Gas-metal effective surface area

P_{SiO} and P_{CO}: Partial pressure of SiO and CO, respectively

a_{Si}: Activity of Si in pig iron

Eq. (2) holds for a unit volume within the furnace.

On the other hand, SiO in bosh gas is supposedly produced by the reduction of SiO_2 contained in coke ash, as well as in slag flowing down through the dropping zone, in the process of coke combustion through eq. (3)[10,12].

$$(SiO_2) + C \longrightarrow SiO\,(gas) + CO\,(gas) \quad \cdots(3)$$

The rate equation for reaction (3) is given by (4)[13].

$$-\frac{\rho_S \cdot H_S}{m_{SiO_2} \cdot A_{SC}} \frac{d[\%SiO_2]}{100dt} = k'_f \cdot a_{SiO_2} \quad \cdots\cdots(4)$$

k'_f: Apparent rate constant of forward reaction

ρ_S and H_S: Density and total hold-up of slag, respectively

m_{SiO_2}: Molecular weight of SiO_2

A_{SC}: Slag-coke effective surface area

a_{SiO_2}: Activity of silica in slag

So far as changes around 1 atmospheric pressure are concerned it has been proved experimentally that the partial pressure of CO does not affect the rate of SiO_2 reduction. If this is taken into consideration, the backward reaction of (3) and reaction (5) may be ignored.

$$(SiO_2) + CO\,(gas) \longrightarrow SiO\,(gas) + CO_2\,(gas) \quad \cdots(5)$$

As is evident from the two reaction rate eqs. (2) and (4), the Si content in pig iron can be controlled in four ways: ① control of reaction temperature (k_f and k'_f), ② control of reaction time (integration in respect to t), ③ control of specific surface area for the reaction (A_{GM}/H_M and A_{SC}/H_S), and ④ control of slag composition (a_{SiO_2}). These four items can be controlled through the methods described below, with the degree of difficulty in execution not considered.

3.1 Control of Reaction Temperature

In view of the following two phenomena, generation of SiO through reduction of SiO_2 and dissolution of Si into pig iron through reduction of SiO, the important factors are the control of SiO generated from SiO_2 contained in the coke ash through control of the temperature of the raceway, that is, the temperature of coke in front of tuyeres, and the control of SiO produced by the reduction of SiO_2 in slag derived from the ore in the dropping zone. The latter is of significance in controlling Si content in pig iron produced through the reduction of SiO_2 in slag by the slag-metal reaction in the dropping zone. At present, the reduction of SiO_2 contained in coke ash to Si in pig iron via SiO is regarded as a greater factor for the determination of Si content in pig iron than the reduction of SiO_2 contained in the ore as gangue materials, though the numeric value of the contribution factor is not known. It is important for explaining Si content in the foundry iron to elucidate this point. In any case, the control of the temperature of coke in front of tuyeres, and that in the dropping zone must be considered. The temperature of combustion gas at the tuyeres is determined by the temperature of coke descending to the raceway, blast temperature, blast humidity, oxygen concentration in blast, and injection of auxiliary fuels such as oil, tar and fine powder coal, and the temperature of the dropping zone is determined mainly by the temperature of combustion gas at the tuyeres, height of dropping zone and flow rate of pig iron and slag. These two temperatures are thus interrelated.

It should be noted here that the theoretical flame temperature in front of the tuyeres which is commonly used as an operational index is determined by the conditions of combined blast alone, and does not always correspond to the actual temperature of combustion gas at the tuyeres.

3.2 Control of Reaction Time

The generation of SiO in the raceway is generally considered to depend upon the temperature of coke in front of the tuyeres and the wetted area between molten coke ash and coke. It may be admitted here to define the reaction time as nothing but the time of stay of hot metal and slag in the dropping zone. The retention time of these liquids depends upon the height of dropping zone, physical properties of liquids (such as viscosity and density), dripping rate, and the particle size distribution of coke in the dropping zone.

If the FeO content of slag melted at a temperature immediately below the cohesive zone (1 400–1 450°C) is high, the dropping distance in which most of FeO is reduced to Fe lowers the height of dropping zone virtually because the partial pressure of oxygen is raised in this region. Accordingly, the height of dropping zone is presumed dependent upon the following factors: temperature of combustion gas in front of tuyeres, ore/coke ratio, melt-down temperature of ore, reducibility of ore (indirect reduction rate within the temperature range from lumpy zone to softening zone), auxiliary fuel injection or moisture in blast (hydrogen content in bosh gas) and heat loss from furnace wall (particularly, heat loss from furnace wall from bosh to bottom).

The retention time of liquids in the dropping zone depends not only upon the height of dropping zone, but also upon the actual velocity of liquid descent. The actual velocity of liquid, V_ℓ, is represented with volumetric velocity, U_ℓ, and total hold-up, H_ℓ, as in eq. **(6)**.

$$V_\ell = \frac{U_\ell}{H_\ell} \quad \cdots\cdots\cdots \textbf{(6)}$$

Since U_ℓ is the volume of liquid passing through unit cross sectional area in unit time, it grows as the specific pig iron output (daily pig iron output per unit volume of furnace) increases through the increase of blast rate per unit time or that of ore/coke ratio.

Consequently, V_ℓ grows, and even if the operation is carried out without changing the height of dropping zone, the retention time of liquid in the dropping zone is shortened.

H_ℓ is represented by eqs. **(7)–(9)** according to Fukutake et al.[14]

$$H_\ell = H_{\ell,s} + H_{\ell,d} \quad \cdots\cdots\cdots \textbf{(7)}$$

$$H_{\ell,s} = \frac{1}{20.5\,\dfrac{0.263\rho_\ell \cdot g \cdot \phi^2 \cdot D_p^2}{\sigma_\ell(1+\cos\theta_\ell)(1-\epsilon)^2}} \quad \cdots\cdots \textbf{(8)}$$

$$\begin{aligned} H_{\ell,d} = 6.05&\left(\frac{\rho_\ell \cdot U_\ell \cdot D_p \cdot \phi}{(1-\epsilon)\mu_\ell}\right)^{0.648} \\ &\times \left(\frac{\rho_\ell^2 \cdot g \cdot D_p^3 \cdot \phi^3}{(1-\epsilon)^3 \mu_\ell^2}\right)^{-0.485} \\ &\times \left(\frac{\rho_\ell \cdot g \cdot D_{p\ell}^2 \phi^2}{\sigma_\ell (1-\epsilon)^2}\right)^{0.097} \\ &\times (1+\cos\theta_\ell)^{0.648} \quad \cdots\cdots\cdots \textbf{(9)} \end{aligned}$$

$H_{\ell,s}$, $H_{\ell,d}$: Static and dynamic hold-up of liquid, respectively (suffix ℓ denotes either hot metal or slag)
D_P, ϵ and ϕ: Particle diameter, void fraction of packed bed and surface factor, respectively, of coke
g: Acceleration of gravity
σ_ℓ and μ_ℓ: Surface tension and viscosity, respectively, of liquid
θ: Contact angle between coke and liquid

When eqs. **(7)–(9)** are applied to a blast furnace of pig iron productivity of 2.0 (t/m^3 · day) or so under the assumption that the physical properties of liquids are not so variable, the static hold-up $H_{\ell,s}$ is much greater than the dynamic hold-up for hot metal, and accounts for 75% of the total hold-up for slag. Hence, H_ℓ is extensively affected by the particle size of coke: the greater the diameter of the particle, the smaller the H_ℓ becomes, with the retention time of liquids in the dropping zone made shorter. For slag, μ_S can be varied widely with the composition, and in some cases, its contribution to H_S should be taken into consideration.

In both hot metal and slag, H_M and H_S are little affected by U_M and U_S, respectively, but retention time is largely affected by U_M and U_S, respectively, as it turns short inversely proportional to the increase in U_M and U_S because of the correlation indicated in eq. **(6)**.

If the particle size of coke in the dropping zone is assumed to be 40 mm or so, a variation of ±10% in the particle size induces a change of ∓16% in H_M according to eqs. **(7)–(9)**. This seems to suggest that the particle size of coke greatly affects the transfer of Si in the furnace via the reaction time. However, the matter is re-examined from another angle, with respect to the specific surface area which is discussed in the following paragraph.

3.3 Control of Specific Surface Area

As shown in eqs. **(2)** and **(4)**, the specific surface areas of reaction for hot metal and slag are given by **(10)** and **(11)**, respectively.

$$a_{GM} = \frac{A_{GM}}{H_M} \quad \cdots\cdots\cdots \textbf{(10)}$$

$$a_{SC} = \frac{A_{SC}}{H_S} \quad \cdots\cdots\cdots \textbf{(11)}$$

As for the reaction between SiO and molten iron in the dropping zone, the effective surface area between gas and liquid, A_{GM}, is calculated by eq. **(12)** according to Bada et al[16].

$$\begin{aligned} A_{GM} = \frac{0.34}{D_p}&\left(\frac{U_M^2}{g \cdot D_p}\right)^{-1/2} \\ &\cdot \left(\frac{D_p \cdot \rho_M \cdot U_M^2}{\sigma_M}\right)^{2/3} \quad \cdots\cdots\cdots \textbf{(12)} \end{aligned}$$

The effects of particle size of coke and metal flow rate to effective surface area are estimated by eq. **(12)** to be proportional to $D_P^{1/6}$ and $U_M^{1/3}$, respectively. And from eqs. **(10)** and **(12)**, in which the contribution of particle size is small, it is assumed that the contribution of particle size increase to the specific surface area a_{GM} is increased nearly by the decrement of H_M. On the other hand, when integrating equation **(2)** with the height of dropping zone and partial pressure of SiO gas held constant, the Si content in produced pig iron is proportional to the product of reaction time by specific surface area. Hence, the relation **(13)** is derived.

$$[\%\text{Si}] \propto \left(\frac{H_M}{U_M}\right) \cdot a_{GM} = \frac{A_{GM}}{U_M} \quad \cdots\cdots\cdots \textbf{(13)}$$

It is presumed, therefore, that the effect of coke particle size to Si content in pig iron is small. The contribution of hot metal flow rate U_M to Si content is expected to be in the order of $U_M^{-2/3}$ from eq. **(13)**.

As for the reaction of SiO generation through the contact of SiO_2 in slag with coke, A_{SC} represents the wetted surface area between slag and coke, to which eq. **(14)** by Onda et al.[17] is applicable.

$$\frac{A_{SC}}{a} = 1 - \exp\left\{-1.45\left(\frac{\rho_S \cdot U_S}{a \cdot \mu_S}\right)^{0.1} \cdot \left(\frac{a \cdot U_S^2}{g}\right)^{-0.05} \cdot \left(\frac{\rho_S \cdot U_S^2}{\sigma_S \cdot a}\right)^{0.2} \cdot \left(\frac{\sigma_C}{\sigma_S}\right)^{0.75}\right\} \quad \cdots\cdots\cdots\cdots (14)$$

a: Specific surface area of coke-packed layer ($\fallingdotseq 6(1-\epsilon)/\phi \cdot D_P$)
σ_C: A constant related to wettability of coke

When estimated on the basis of operational conditions of specific pig iron productivity mentioned above, the effects of coke particle size and slag flow rate to A_{SC} are proportional to $D_P^{-0.7}$ and $U_S^{0.4}$, respectively. If the height of dropping zone and the quantity of bosh gas are held constant, the partial pressure of SiO gas generated is proportional to the product of decrement of SiO_2 content in slag with flow rate of slag. As in the case of **(13)**, the following equation is derived in consideration of the integration of eq. **(4)**:

$$P_{SiO} \propto \left(\frac{H_S}{U_S}\right) \cdot a_{SC} \cdot U_S = A_{SC} \quad \cdots\cdots (15)$$

The contributions of coke particle size and slag flow rate to SiO content generated in unit time at the dropping zone are, therefore, estimated to be in order of $D_P^{-0.7}$ and $U_S^{0.4}$, respectively. The correlation of these parameters to the operational data of the blast furnace is not known.

3.4 Control of Slag Composition

As stated above, there are two possible sources of SiO. The chemical composition of coke ash is nearly constant, and it seems to be almost impossible to change it in consideration of chemical composition of imported coal. It is rather difficult to control the generation of SiO from the coke ash via the chemical composition. The more practical method is to change the quantity of ash, though the variable range is limited. On the other hand, the slag derived from the gangue of ore can be controlled by adjusting the basicity of gangue components in the sinter and pellet, for instance.

In view of the possibility that SiO of high partial pressure generated around the tuyeres is absorbed by dripping slag while ascending through the dropping zone, the control of the basicity of gangue components in sinter and pellet changes the rate of SiO absorption in the dropping zone, and hence, results in the control of SiO partial pressure.

The methods of controlling the Si content in pig iron for various factors are represented by a block diagram in **Fig. 3**.

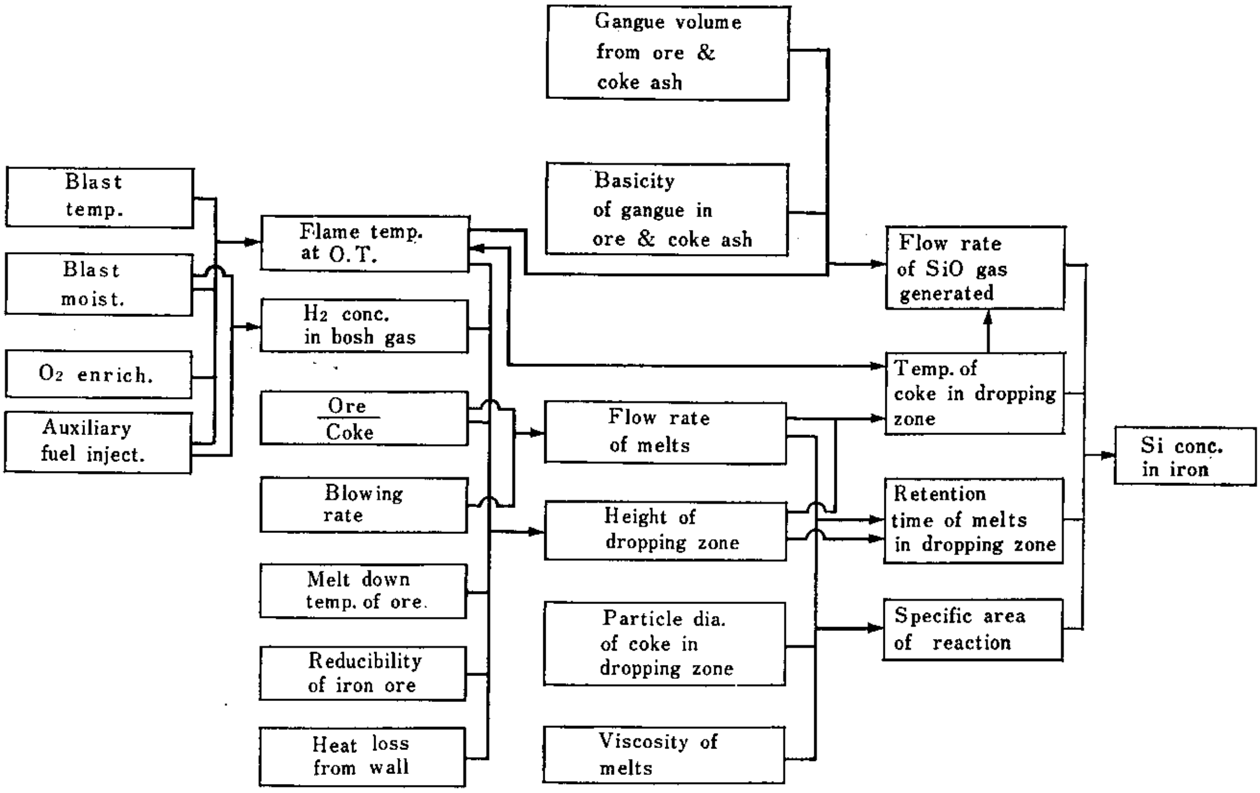

Fig. 3 Flow diagram of deciding factors on Si concentration in pig iron

4 Features of Blast Furnace Operation vs. Si Content in Pig Iron

4.1 Short-time Relationship

The essential requirements for the blast furnace operation are to ensure smooth tapping operation and constant composition of pig iron. One of the most important operational indexes is the temperature of hot metal. In view of short-time fluctuations, the temperature and Si content of hot metal vary with the heat accumulation at the lower part of the furnace, which is to be designated as thermal state. As for the relationship of hot metal temperature to Si content, for instance, for the continuously tapping data, as shown in **Fig. 4**, the Si content has high positive correlation with the hot metal temperature, changing by ±0.03–0.05% for ±10°C. In order to prevent variation of Si content, the primary pre-requisite is to stabilize the hot metal temperature level. However, controlling the thermal state after establishing the hot metal temperature results in retardation of Si content control. For short-time control of Si content, therefore, the effective means is to change the blast and burden conditions on the basis of heat H_0 used for processes other than dissociation of iron oxide into iron and oxygen, as calculated on the basis of heat and materials balance in the blast furnace from moment to moment. **Fig. 5** shows changes in time of H_0 and Si content, and **Fig. 6** changes in the correlation coefficient with respect to delayed time between H_0 and Si. **Figs. 5** and **6** show that the Si content at the time of tapping is strongly correlated with H_0 two hours before, and the usefulness of taking operational action while monitoring H_0.

More drastic changes in Si concentration occur in a short time in cases where the burden descent is retarded by decrease in blast rate or blast pressure, or the burden descent is accelerated by bringing unreduced ore into the hearth. These are related to a decrease or increase in dropping rate of pig iron U_M produced in the furnace. That is, in consideration of Si absorption in pig iron, the effect of hot metal flow rate on the reaction surface area is small as shown in eq. **(12)** and **(13)**, largely depending upon change in the retention time in the dropping rate. In this way, when the burden descent rate fluctuates extensively, an average Si content in pig iron varies greatly. Under the circumstances, as the operation in a higher thermal state is performed to secure heat accumulation, the Si concentration rises. **Fig. 7** shows a high positive correlation between the fluctuation of blast pressure and that of Si concentration in place of the burden descent rate fluctuation.

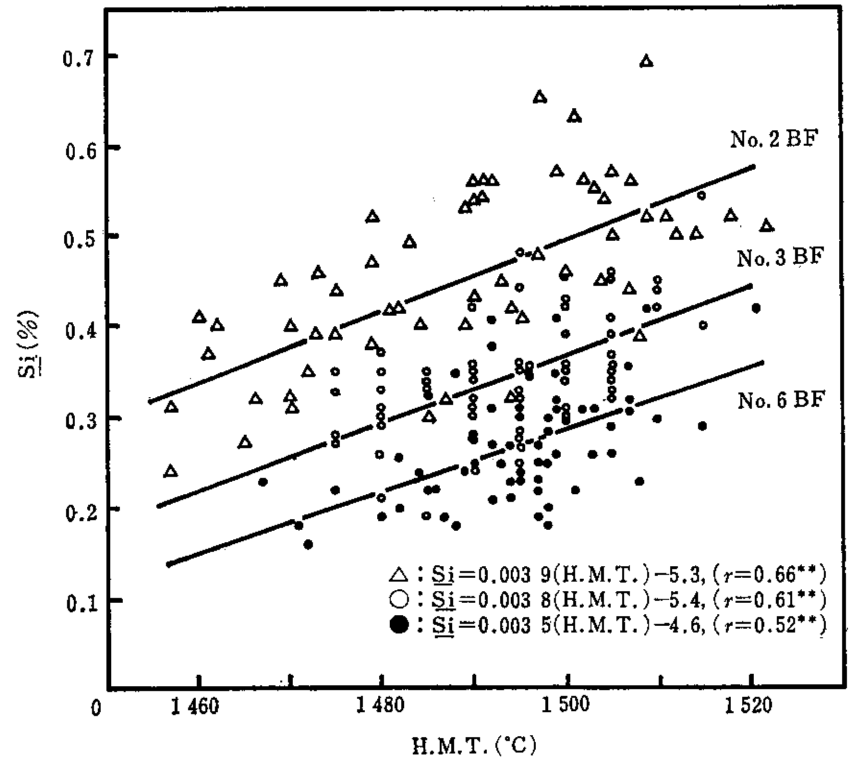

Fig. 4 Relation between Si content in pig iron and hot metal temperature (H. M. T.) in each blast furnace at Chiba Works

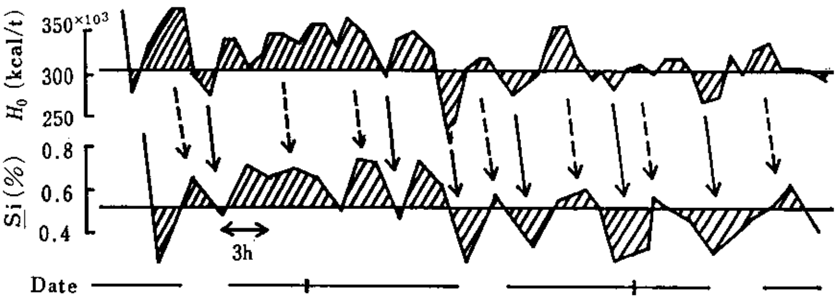

Fig. 5 An example of variation of H_0 and Si content with time (Chiba No. 6 BF)

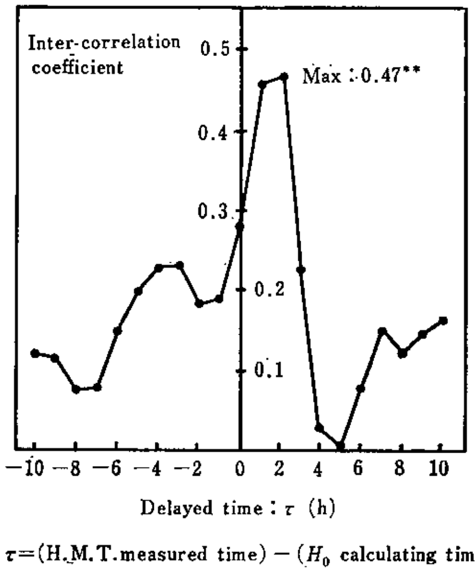

Fig. 6 Variation of inter-correlation coefficient between H_0 and Si content with delayed time

4.2 Long-time Relationship

Fig. 8 shows that the long-time variation in the Si concentration level is caused by lowering the height of dropping zone due to the improved utilization of gas, for instance, in a particular blast furnace. In **Fig. 8**, V_d is the volume of dropping zone calculated with a model of coaxially divided blast furnace[18], to be corresponded to the mean height of dropping zone.

Besides, there is a case where Si concentration level is low despite the same hot metal temperature level and nearly identical specific iron output and blast conditions. **Fig. 9** shows the relationship of hot metal

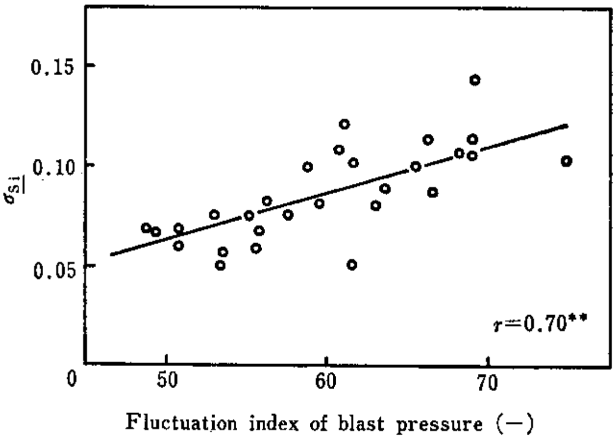

Fig. 7 Influence of fluctuations of blast pressure on σ_{Si} at Chiba No. 6 BF (Fluctuation index; corresponding to a daily sum of fluctuation values)

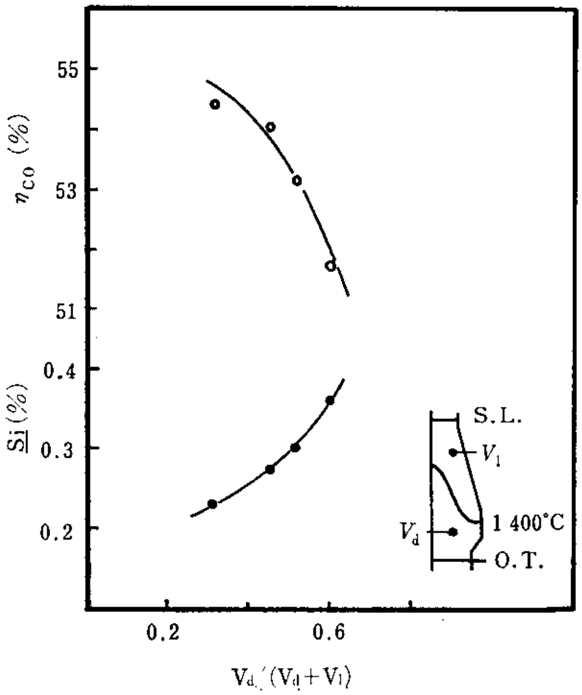

Fig. 8 Changes of Si content in pig iron and of CO gas utilization with the fractional volume of dropping zone (Chiba No. 6 BF)

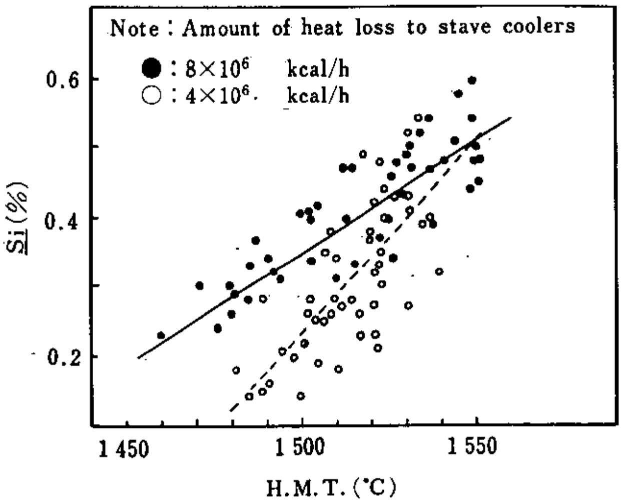

Fig. 9 Influence of the amount of heat loss to stave coolers on the relation between Si content and hot metal temperature at Chiba No. 6 BF

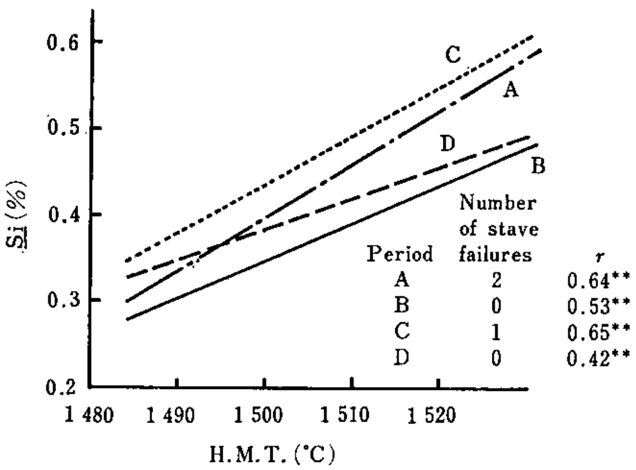

Fig. 10 Difference of the relation between Si content and hot metal temperature during 10 days periods at Mizushima No. 3 BF

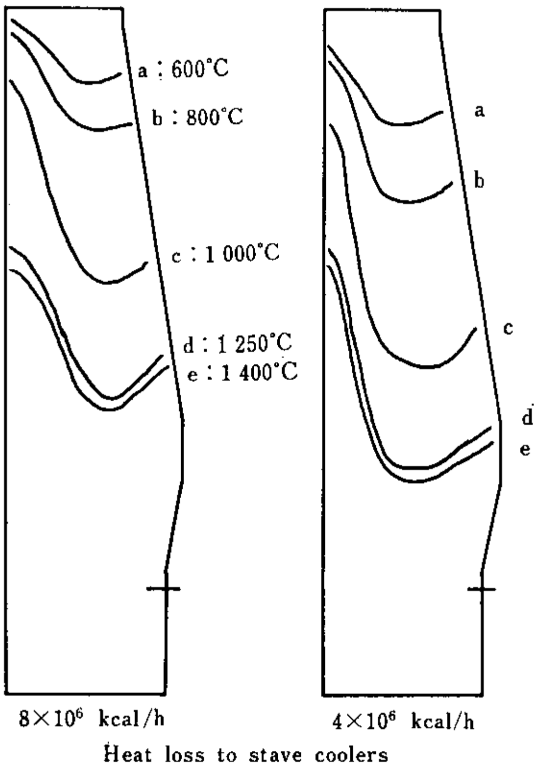

Fig. 11 Calculated temperature distributions in a blast furnace corresponding to heat loss to stave coolers

temperature stratified by the heat flux to stave cooler with Si concentration in the No. 6 BF at Chiba Works. When the heat flux to stave cooler is low, the Si content level is also low. A similar relation is found in the No. 3 BF at Mizushima Works, too (**Fig. 10**). In this case, data on the thermal flux are not available. In periods A and C, stave failure occurred, and the temperature of furnace wall from the lower part of the shaft to the belly was high, being in a similar situation as in the period of higher heat flux to stave cooler in **Fig. 9**. If the correlation of difference in heat flux shown in **Fig. 9** to conditions in the furnace is examined by using the model of co-axially divided blast furnace mentioned above, the temperature profiles in the furnace may be drawn as in **Fig. 11**. It is evident from **Fig. 11** that if the temperature level at the melting zone in the vicinity of the furnace wall is high, the heat flux to stave cooler is also high. That is, the profile shows that the temperature within the furnace changes abruptly across the melting zone, rising very high below the zone and the heat transfer to the furnace wall in the lower part of shaft is greatly affected by the level of the melting zone. The reason why the Si content is affected by the difference in heat flux to stave cooler will be described in the following subsection.

Elsewhere, as the blast furnace productivity rises, the Si content falls, and the comparison at the same hot metal temperature level in the recent all-coke operation indicates that the Si content increases in correspondence to an increase in SiO production in front of the tuyeres due to the increase of coke burnt in this zone. For the latter, the hot metal temperature is to be lowered after being changed over to all-coke operation.

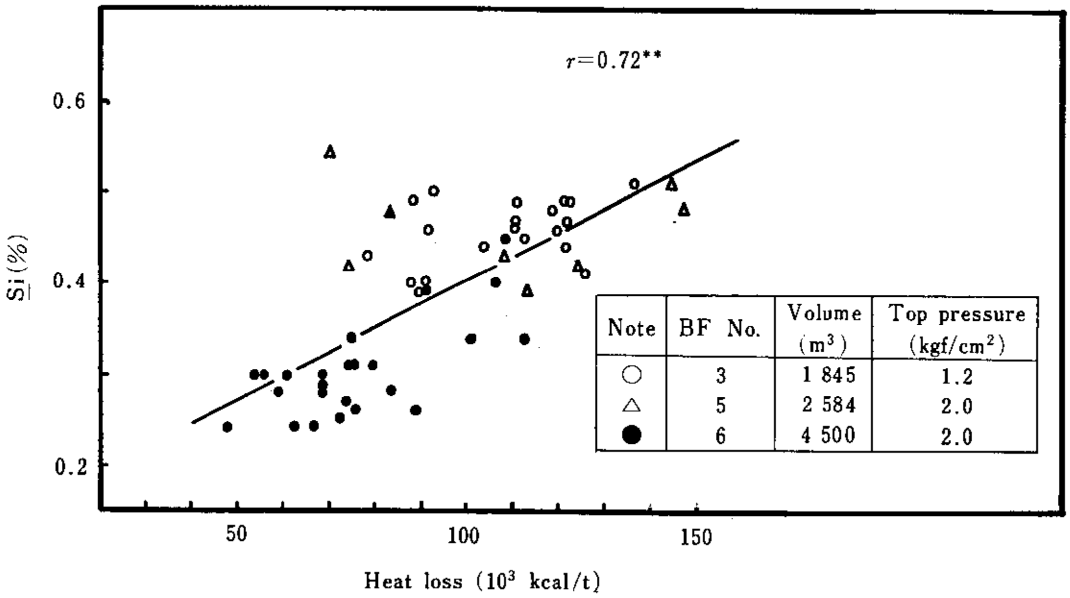

Fig. 12 Influence of heat loss from high temperature region above 950°C on Si content in pig iron (Chiba Works)

4.3 Effect of Inner Volume of Blast Furnace

It is generally recognized that Si content is lowered as the inner volume is expanded. Up to now, this has been interpreted in various ways: ① rise of CO partial pressure due to high top pressure, ② decrease in retention time of hot metal at the dropping zone due to increased mass flow rate of descending hot metal, and ③ relative contraction of high temperature region in the vicinity of raceway in respect of sectional area of the hearth. As stated in the preceding paragraph, the absorption of Si in pig iron is greatly affected by the heat balance at the lower part of the furnace. The advantage of expanded inner volume for the heat balance at the lower part of the furnace is considered to be a reduced heat loss from the furnace wall. In **Fig. 12**, the heat loss from the furnace wall is calculated on the basis of heat balance in the 10-day average operational data and plotted against the Si content. From **Fig. 12** it is evident that the Si-content level is not stratified by furnace volume and top pressure, but uniquely related to the heat loss from the furnace wall. The same relationship is obtained when plotted against the heat input per ton of pig iron. That is, in order to produce pig iron of lower Si concentration, it is essential to reduce the heat input to the lower part of the furnace as far as possible while keeping the hot metal temperature constant.

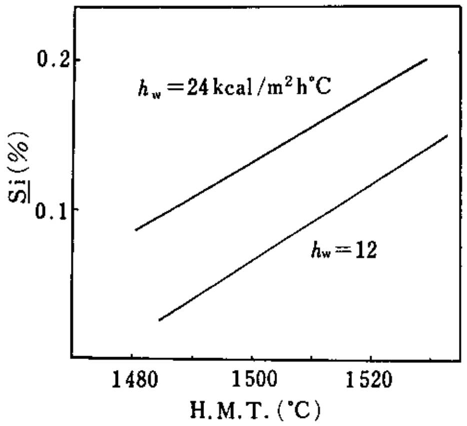

Fig. 13 Relation between Si content in pig iron and hot metal temperature by calculation

5 Limit of Low-Si Pig Iron Smelting in Blast Furnace

5.1 Estimation of Si Content Attainable in Future

In **Fig. 13**, the relationship of hot metal tapping temperature to Si content in tapped iron is calculated and graphically represented by using equations on the method of smelting low-Si pig iron mentioned in Section 3, and differential balance equations on the heat transfer between gas phase–solid phase–metal phase–slag phase*.

As for the apparent rate constant of forward reaction in eqs. **(2)** and **(4)**, k_f is given by **(16)** on the basis of data of experiment of reaction between carbon-saturated iron and SiO gas according to Tsuchiya et al.[11] and k_f' by **(17)** on the basis of data of experiment of reaction between graphite and blast furnace-type slag according to Sumito et al.[19] (Unit: $kmol/m^2 \cdot h$)

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* Details of mathematical treatment will be described elsewhere.

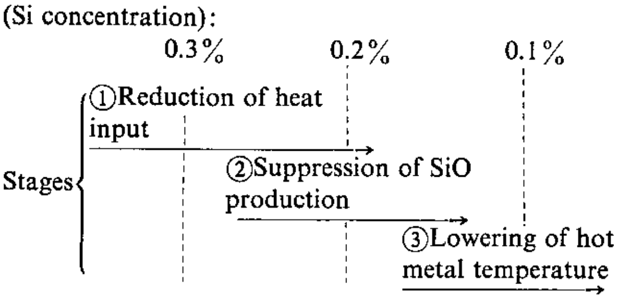
$$k_f = 4.77 \times 10^8 \exp\left(\frac{-66\,500}{RT}\right) \quad \cdots\cdots(16)$$

$$k'_f = 1.785 \times 10^{17} \exp\left(\frac{-177\,000}{RT}\right) \quad \cdots\cdot(17)$$

SiO_2 contained in coke ash is assumed to enter rapidly into gas phase as SiO until the temperature of coke at the raceway becomes equal to the melting point on the phase diagram[20] of ash composition. In **Fig. 13**, $h_W = 12$ kcal/m²·h·°C represents the heat transfer coefficient to the furnace wall. This corresponds to a heat loss from furnace wall of 10^5 kcal/t-pig iron in case of a blast furnace with 10 m hearth diameter. According to this calculation, SiO_2 contained in slag descending through the dropping zone gives very little SiO, and most SiO is derived from SiO_2 in coke ash. The applicability of eq. **(17)** to an intact use for the blast furnace dropping zone leaves some room for study as the equation is still under examination as the formula for the rate of reaction between the graphite crucible and SiO_2 in slag. Anyway, paradoxically speaking, it is presumed that if the furnace is operated under conditions where SiO_2 in coke ash produced in front of the tuyeres alone is responsible for the Si transfer in the furnace, the Si content of hot metal at 1 500°C can be reduced to 0.1% or less. When discussing a Si concentration as low as 0.1%, it is possible that the Si transfer due to the slag-metal reaction at the liquid bath in the hearth can not be ignored[21]. However, up to now, when pig iron of 0.2% Si content can be obtained at 1 500°C, it has not been proved that the slag-metal reaction defines the limit of reducing the Si concentration.

In the relationship of hot metal temperature to Si content shown in **Fig. 13**, the Si concentration rises despite the same hot metal temperature if the heat transfer coefficient to the furnace wall is increased, that is, if the heat loss from the furnace wall is increased. In any case, the Si content of pig iron derived from SiO gas is very small at 1 450°C or lower.

To sum up the results mentioned above, the limit of reducing Si concentration in the blast furnace may be schematically represented below.



That is, Si concentration can be reduced from 0.2% to 0.1% by improving the properties of slag and coke and controlling the temperature of coke in the dropping zone while maintaining the currently available operational technique of reducing heat input. In the future, Si concentration lower than 0.1% will be challenged, aiming at a hot metal temperature of 1 450°C or so. Factors to be taken into consideration at various stages shown in **Fig. 3** are the retention time of liquid in the dropping zone for Stage ①, properties of ore and coke and temperature of combustion gas in front of the tuyeres for Stage ② and the distribution of coke temperature in the dropping zone (distribution of hearth heat) for stage ③.

5.2 Problems in Technology of Producing Low-Si Pig Iron

The execution of low-Si pig iron smelting mentioned in the preceding paragraph involves three problems to be solved in the future. First, the reduction of heat input lowers the melting zone level in the furnace, and if the latter level is too low, the burden descent becomes unstable. This phenomenon may occur even in cases where the radial distribution of melting zone is reduced while keeping good balance, unreduced ore is not brought into the hearth, and the composition of pig iron is stabilized. The countermeasures for this phenomenon will be considered through the dynamic analysis of burden descent. The Second it is necessary to devise methods of independently controlling the coke temperature and the tapping metal temperature which are presumed to greatly affect the reaction rate of SiO production. For this purpose, it is necessary to elucidate quantitatively the mechanisms of heat transfer to hot metal and slag at the lower part of the furnace, and of Si transfer reaction. Third and final, the problem of built-up or dirty hearth caused by the overall heat insufficiency in the hearth region. Particularly, for keeping the hot metal temperature at a lower level for a long period, it is very important to maintain stable properties and particle size of blast furnace burden, and special attention is required for the control of melt-down characteristics of burdened ore and properties of final slag.

6 Conclusion

The method of smelting low-Si pig iron was examined from the viewpoints of chemical reaction and chemical engineering, in consideration of recent trends of Si concentration in pig iron produced by blast furnaces at Chiba and Mizushima Works. Made clear as a result were the importance of ① stabilization of furnace conditions by suppressing the variation of burden descent rate and ② lowering the height of dropping zone and suppressing the generation of SiO around the tuyeres by reducing heat input as far as possible while maintaining the hot metal temperature at a fixed level. Also, for reducing heat input, it was found important to reduce heat loss from the furnace wall, in view of the effect of furnace volume.

While effects up to now have made it possible to smelt pig iron of Si content 0.20% or so, the target Si concentration in the near future was estimated at 0.10% or lower and the problems to be solved for attaining this target were discussed.

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