Lower Limit of the Energy Consumption and the Double Ignition Process for Iron Ore Sintering*

By Shun SATO,** Takazo KAWAGUCHI** and Masakazu KATO***

Synopsis

The lower limit of energy consumption in the actual iron ore sintering process was investigated by experiments and a simulation model. The energy consumption was reduced with the decrease in the induced air volume and in the coke breeze content in raw mix. Under the condition of maintaining the sinter yield more than 60 %, the lower limit of the energy consumption was achieved at an induced air volume of $9 \text{ Nm}^3/\text{m}^2 \text{ min}$, and a coke content of 2.6 wt% in sinter mix. This condition corresponds to the heating to the maximum temperature of more than 1250°C and the holding at high-temperatures above 1100°C over 5 min.

For the improvement of the utilization efficiency of oxygen, that is, the reduction of unit air volume, the application of the double ignition sintering was investigated. Under the conditions of the high bed height and high suction pressure, the sinter productivity reached to about $57 \text{ t}/\text{m}^2 \text{ D}$ and a slight reduction of energy consumption was accomplished, if the sinter strength values of 50 to 60 (TI) are allowable.

Key words: agglomeration; sinter; iron ore; combustion; energy saving; sintering.

I. Introduction

The energy consumption in the sintering process was mainly composed of the coke breeze consumption and the fan electricity. When further energy saving in the sintering process is intended, investigation of the lower limit of energy consumption in the actual sintering process is indispensable.

Wendeborn and Cappel¹⁾ showed that the minimum coke breeze content in raw mix was 2.5 wt% (150 kcal/kg-dry mix) as a result of heat transfer experiment with an inert medium. Recently Nigo *et al.*²⁾ estimated the lower limit of coke breeze content to be 2.3 wt% on the basis of a mathematical simulation model for sintering operation. However, the above values were estimated on the assumption of constancy in the induced air volume. Conditions for the lowest energy consumption should be found from the consideration of both coke breeze content and induced air volume in sintering.

Secondly, the decrease of suction pressure and induced air volume in a sinter exhaust fan significantly reduces the electricity consumption in sintering. There are important problems on the unit air volume and the balance between the combustion rate and the heat transfer rate under a low sinter productivity. Voice and Wild³⁾ estimated the necessary unit air volume as $850 \text{ Nm}^3/\text{t-sinter mix}$ and the necessary oxygen content as more than 9.0 vol% in induced air

as the result of experiments on the relationship between induced air volume and heat transfer rate in an inert medium as well as in iron ore sintering. However, it is still unknown whether their findings are valid or not (even if) in very lower flow region.

Moreover, in the ordinary sinter operation, the amount of unreacted oxygen is about 15 vol% in the exhaust gas. Thus about a half of the induced air was not utilized in the sintering process and was exhausted along with its sensible heat. Therefore, a gas circulation process⁴⁾ and a double ignition process⁵⁾ for more effective utilization of oxygen have been examined to reduce the induced air volume.

The present research was carried out to investigate the lower limit of energy consumption in the actual sintering and to estimate the merit of the double ignition process in sinter experimentally.

II. Experimental Procedure and Mathematical Simulation Model

1. Evaluation of the Lower Limit of Energy Consumption

The lower limit of energy consumption was investigated by the use of a pot apparatus shown in Fig. 1. The iron ore materials were prepared with a variety of coke content by adding the mixture collected from an actual sintering plant before coke breeze mixing. The materials were mixed in a batch-type horizontal mixer (400-mm diameter, 600-mm length and a rotating speed of 25 rpm) for 3 min and were granulated adding a proper amount of water for 3 min. The granulated mixture was charged into a 300-mm diameter standard sintering pot with a bed height of 380 to 930 mm and was ignited by a propane gas burner. Afterwards the sintering was carried out at a constant suction pressure of 2.0 to 11.8 kPa controlled with the valve of the exhaust fan. Fine sand was inserted onto the periphery of the pot to avoid the leakage of air and to ensure the uniform flow of air in the bed.⁶⁾ The induced air volume was mainly measured by an orifice on the rectifying hood with a calibrated turbo-anemometer with satisfactory accuracy especially in the lower flow-rate region. The progress of sintering was monitored with the downstream gas analysis and the three pairs of Pt-Pt-Rh13% thermocouples horizontally inserted into the bed.

* Based on the papers presented to the 113th ISIJ Meeting, April 1987, S109 and S110, at The University of Tokyo in Tokyo. Manuscript received on November 5, 1987; accepted in the final form on April 15, 1988. © 1988 ISIJ

** Iron and Steel Research Laboratories, Sumitomo Metal Industries, Ltd., Sunayama, Hasaki-cho, Kashima-gun, Ibaraki Pref. 314-02.

*** Head Office, Sumitomo Metal Industries, Ltd., Kitahama, Higashi-ku, Osaka 541.

2. Test of the Double Ignition Sintering

In the sinter pot test, a half portion of iron ore materials was charged into the pot as the lower layer and was ignited by the burner. Afterwards the remaining material was immediately charged as the upper layer and was ignited similarly. The sintering advanced simultaneously in both layers by induced air through the bed. The induced air composition was changed by introducing a mixed gas of oxygen, nitrogen and water vapor from the top of bed and measured by an infrared gas analyzer to be controlled at a predetermined value.

The practical image of the double ignition sintering was schematically shown in Fig. 2. Based on the findings obtained from the pot test, the test of double

ignition process was extended to a Dwight Lloyd-type (DL) test machine,⁷⁾ with an effective area of 3.5 m², a pallet width of 0.4 m, and the maximum capacity of 3.5 t/ch, which was provided with two pairs of charging devices and ignition furnaces. The test conditions and the composition of raw materials were shown in Table 1.

Influences of the induced gas composition and the oxidized material content, and effects of oxygen enrichment and sinter qualities were studied in the pot test. The ordinary sintering and the double ignition process were compared in the DL test machine for the energy consumption and productivity of sintering.

3. Mathematical Simulation Model

For the theoretical estimation of the lower limit of energy consumption and the merit of double ignition sintering, a mathematical simulation model⁸⁻¹⁰⁾ was used. The following fundamental equations on combustion and heat transfer were employed in the model for the conditions given in Table 2.

Enthalpy balance on gas:

$$C_g \cdot G \cdot \frac{\partial T}{\partial z} = A \cdot h \cdot (T - t) + (1 - \alpha) \cdot \Delta H_c \cdot R_c$$

.....(1)

Fig. 1. Test apparatus and test conditions.

Fig. 2. Schematic image of the double ignition sintering.

Table 1. Test conditions and raw materials employed.

1. Test conditions P : Suction pressure (kPa), C : Coke content (%), H : Bed height (mm)							
Test items	Apparatus	Layer(s)	Materials	Sintering			
Change in air composition	Pot (300 ϕ)	Single	In-plant sinter mix	P : 9.8, C : 2.7~3.3 H : 500			
O ₂ consumption of mix	Pot (300 ϕ)	Single	In-plant mix & Blend A, B	P : 9.8, C : 2.4~5 H : 500			
Sinter qualities	Pot (300 ϕ)	Single & double	Blend A	P : 11.8, C : 3.4~4 H : 500~1000			
Comparison 1 (Energy saving)	DL test machine	Single & double	In-plant sinter mix	P : (S) 8.3, (D) 11.0 H : (S) 410, (D) 750			
Comparison 2 (High productivity)	DL test machine	Single & double	Blend A', B'	P : (S) 15.4, (D) 19.0 H : (S) 460, (D) 750			
2. Raw materials (wt%)							
	SF Hamersley	SF Rio Doce	Return fine	Limestone	Quick lime	Scale	Ni slag
Blend A	30.0	30.0	30.0	10.0	—	—	—
B	28.5	28.5	30.0	10.0	—	3.0	—
A'	30.0	30.0	28.5	9.0	1.0	—	1.5
B'	29.0	29.0	28.3	7.2	2.0	3.0	1.5
In-plant sinter mix	T.Fe: 51.0 %, FeO: 6.1 %, CaO: 9.6 %, SiO ₂ : 4.8 %, C.W: 1.8 %						

Table 2. Calculating conditions for sinter simulation model.	
Materials	$d_p=0.003\text{ m}$, $d_c=0.00134\text{ m}$, $\epsilon=0.35$, $JPU=22.0$
Air	$[O_2]=0.2072$, $[N_2]=0.7784$, $[H_2O]=0.0144$
Ignition	1 427°C, 1.5 min
Coke combustion rate constant	$K_c=6.42\times10^{11}\cdot T_c^{-1/2}\cdot\exp(-44\,000/RT_c)$
α : Heat distribution ratio (=0.21)	
Change in coefficient of flow resistance	
$F_1=F_{1m}+(F_{1s}-F_{1m})\cdot Q$	
$F_2=F_{2m}+(F_{2s}-F_{2m})\cdot Q$ (Q : melting ratio)	
$A=A_m+(A_s-A_m)\cdot Q^{1/2}$	

Enthalpy balance on materials:

$$\begin{aligned} (1-\epsilon)\cdot\rho_s\cdot C_s\cdot\frac{\partial T}{\partial\theta} &= A\cdot h\cdot(t-T)+\alpha\cdot\Delta H_c\cdot R_c \\ &\quad -\sum_{i=1}^n\Delta H_i\cdot R_i \dots\dots\dots(2) \end{aligned}$$

Combustion rate of coke:

$$R_c=W_c\cdot\frac{\partial f_c}{\partial\theta}=6(1-f_c)^{2/3}\cdot\frac{W_c}{d_c}\cdot K_c\cdot[O_2] \dots\dots\dots(3)$$

Pressure drop in bed:

$$=F_1\cdot\mu_g\cdot U+F_2\cdot\rho_g\cdot U^2 \dots\dots\dots(4)$$

Convection was only considered as the heat transfer process, and the combustion heat was distributed between gas and material with a specific ratio α . The reaction rate constant of coke combustion was calculated from Parker and Hottel's equation.¹¹⁾ The reaction heats of water vaporization, thermal decomposition of limestone and melting of material were considered. The pressure drop in bed was introduced on the basis of Ergun's experimental equation¹²⁾ and the flow resistant coefficients were calculated according to the progress of melting.

III. Experimental Results and Discussion

1. The Limit Condition of the Sintering Process

1. Air Volume and Flame Front Speed

Variations of induced air flow rate, the exhaust gas temperature and the gas composition throughout the sintering process in a typical pot test were described in Fig. 3. The induced air flow rate and the exhaust gas temperature remained almost constant after ignition and started to rise after the flame front reached to the bottom of the layer because of the completion of dehydration of sinter mix. The transition time is called as the flame front point (FFP). Afterwards the exhaust gas temperature reached to the maximum, burn through point (BTP), indicating the completion of the sintering reaction.

The exhaust gas contains a small amount of CO, a significant amount of CO₂ and the unreacted oxygen retained from the induced air at the steady state of

Fig. 3. Changes in measured exhaust gas composition, temperature and induced air flow rate in pot test with sand seal.

sintering. If the oxygen in the induced air was completely utilized for combustion, the air volume necessary for sintering would be reduced to about a half of the present value. After the coke combustion was completed at the FFP, the gas shows the same composition as the induced air.

The total gas balance during sintering is shown in Table 3. The fraction of air utilized for coke combustion to the total volume of induced air was about 60 vol% and the remaining part of air contributed only as the medium of convection heat transfer. The magnitude of this unit air volume was somewhat smaller in comparison with the Voice and Wild's measurement³⁾ because of the difference in gas sealing. However, the leak air of 70 Nm³ for dry material (about 9 vol% in total) still remained. The gas was exhausted of 66 vol% for coke combustion, 25 vol% for cooling and 9 vol% in leakage. Though the required unit air volume is about 1 200 Nm³ for a unit dry material in the present commercial sintering machine, sintering can be performed as an ideal case with a half of unit air volume on the basis of the present results. In this ideal case, a great decrease of the induced air volume significantly reduces the electricity in sintering along with the decrease in the suction pressure.

The correlation between induced air flow rate and sintering speed under various suction pressures with and without sand seal is shown in Fig. 4. The sintering speeds were indicated by two indices: the descending flame-front speed (FFS) of the isothermal plane in heating and the descending flame-behind speed (FBS) of the isothermal plane in cooling. In each case, the sintering speed had the positive linear correlation with the air flow rate over a wide range of air flow rate. The FFS is greater than the FBS in the range of the present experiments. The FFS and the FBS are slightly different in the range of low air flow rate and coincident at the zero air flow rate. How-

Table 3. Balance of sintering gas in pot test
(at F.C.=3 %, FFS=20 mm/min).

Combustion air	220	(Nm ³ /Mix-t)
Others	150	
Induced air	370	
H ₂ O+Decomposition CO ₂	120	
Before FFP	490	
After FFP (till BTP)	184	
Sintering gas	674	
Leakage air	70	
Total exhaust gas	744

Fig. 4. Relation between sintering speed and induced air in pot test.

ever, the extrapolation of the sintering speed to the zero air flow rate lead to non-zero. This implies that other factors than the air flow contribute to the sintering speed.

The experimental result that the correlation line between air flow rate and sintering speed does not pass the origin may be a result of the change in the ratio of air flow rate to sintering speed associated with the change in air flow rate. Accordingly, the unit air volume per dry materials decreases with decreasing air flow rate as shown in Fig. 5. The unit air volume, calculated by a simple equation shown in the figure, becomes smaller when the induced air flow rate becomes lower. Consequently the electricity per sinter product would be smaller in the lower range of induced air flow rate than in the higher range, even if an actual sintering machine was insufficient in prevention of leak air.

2. Sinter Yield and Sintering Limit

Secondly the lower limit condition is discussed from the viewpoint of energy consumption.

The lower limit of energy consumption is determined by optimized lower limit of both coke content and air flow rate by maintaining good sinter. First of

Fig. 5. Relations between induced air and air volume consumption.

Fig. 6. Simulation result of relation between distance from bed surface and maximum temperature in bed.

all the influence of the bed height on the maximum temperature in bed was calculated from the simulation model for sintering. Figure 6 shows the maximum temperature in bed calculated for a fixed carbon of 3.0 wt% and an induced air flow rate of 12 Nm³/m² min. Since the maximum temperature in bed has to be maintained above 1 300°C⁽¹³⁾ (average temperature: 1 250°C) for the production of good sinter, the bed higher than 380 mm was required. Therefore, the lower limit of sintering process was studied in the following for a constant bed height of 380 mm.

In Fig. 7 the isothermal lines of the maximum temperature in the bed and the isochronal lines of the holding time at high temperatures above 1 100°C are described against the change in coke content and suction pressure. The temperature in bed elevates when the coke content is increased and the suction pressure is decreased. However in the range of a low suction pressure together with a low coke content, the stable operation keeping high temperatures seemed difficult.

Sinter yield improves with elevated temperature of the bed and prolonged holding at the high temperature zone. On the basis of the results of the model simulation, sinter pot tests were carried out. Based on the comparison between the calculated results and the observed ones, conditions to achieve the lower limit in actual sintering process were discussed in Fig. 8. The calculated maximum temperature in bed is

shown by solid lines and the calculated holding time at high temperature zone by broken lines in the figure plotted against the coke content and the suction pressure. The sinter yield in the sintering pot tests was plotted by different marks for three yield levels. The requirement for sinter yield above 60 % is the maximum temperature higher than 1 250°C and the holding time at high temperature zone (1 100°C) longer than 5 min.

Consequently the conditions for permissible lower limit in actual sinter were 2.6 wt% of the coke content and 9 Nm³/m² min of the induced air flow rate. Alternatively at a lower limit of coke content of 3.0 wt%, the decreased induced air flow rate as low as 5 Nm³/m² min becomes feasible. In the model simulation the lower limit level of the induced air flow rate was not fully clarified and the stable operation of sin-

tering seemed difficult owing to the proximity of the isothermal lines in the range of the lower coke content and the lower air flow rate as shown in Fig. 7. From the results of the sintering pot test, unstable burning was shown to arise predominantly in that range and the sinter yield also decreased.

When the sinter is operated under the lower limit condition, low energy consumption in the sintering will be obtained such that coke consumption is about 30 kg/t and electricity of the exhaust fan is about 5 kWh/t. However, in this case the sinter productivity takes the lower value of about 12 t/m² D.

2. The Double Ignition Sintering Process

1. Influence of the Induced Gas Composition

The gas compositions which may affect the coke combustion in the lower layer are the oxygen content and water vapor content at the bottom of the upper layer. The influences of two gas components on the FFS and the sinter strength (*TI*) are shown in Fig. 9. The water vapor hardly influences the sintering reaction, while the decrease of oxygen content in gas aggravates both the FFS and sinter strength.

Especially the decrease of sinter strength was remarkable below the oxygen content of 15 vol%: the allowable strength should exceed 50 in the pot test. The problem has been also confirmed on the exhaust gas circulating process¹⁴⁾ in sintering and was considered as the decrease of the bed temperature and the reduction of holding time at high temperatures due to the restraint of coke combustion with low oxygen content. In ordinary sintering the water vapor content is about 10 vol% and the oxygen content is about 12 to 15 vol% in the exhaust gas. Consequently it is important that the oxygen consumption is suppressed as low as possible in sintering in the upper layer to keep the sinter strength of the lower layer in the double ignition sintering.

2. Influence of Mill Scale on Oxygen Consumption

In Fig. 10 the correlation between the coke content and the oxygen content in sintering gas is shown in the case of mill scale addition. Besides the unreacted portion, most of oxygen in air was consumed by coke combustion and the oxygen content in exhaust gas decreased with increase of the coke content in mix. When oxygen was consumed by the material other

Fig. 7. Simulation result of changes in maximum temperature and in high-temperature holding time in bed influenced by coke content and pressure drop per bed height.

Fig. 8. Results of sinter pot tests (bed height 380 mm) and heat pattern lines calculated by the model.

Fig. 9. Influence of induced air composition (H₂O, O₂) on *TI* and FFS for single ignition sintering.

Fig. 10. Relations between O_2 content in sintering gas and coke content in bed in single ignition sintering.

than coke in mix like mill scale as in the actual raw material mix, the oxygen content in the exhaust gas becomes lower. The oxygen content was reduced to 3.1 vol% for the unit change in coke content and 0.5 vol% for the mill scale content. The results were in good agreement with the values predicted from stoichiometry.

Consequently, to ensure the double ignition sintering, the sum of oxygen consumption in both layers should be less than 21 vol% and, in the case of equally dividing into each layer, the oxygen consumption in each layer should be less than 10.5 vol%. This means that the higher limit of coke content is 3.4 wt% in a mix without mill scale and is needed to reduce according to the mill scale content as shown in Fig. 10. Thus, the coke content is severely restricted in the double ignition sintering.

In Table 4, the theoretical calorific value (A), the theoretical oxygen consumption (B) and their ratio (A/B) per unit weight of coke and mill scale are shown. In the double ignition sintering, the material with a larger value of (A/B) is advantageous and, in this sense, the mill scale is more effective than coke. Consequently, it is highly desirable to use mill scale as much as possible and to suppress the coke content in accordance with the calorific value. As the other calorific supplement, the substitution of limestone to quick lime is considered effective.

3. Influence on Sinter Qualities

Sinter qualities both in ordinary sintering and in double ignition sintering are shown in Fig. 11. The sinter strength (TI) is nearly identical between the two processes in the upper layer, while the strength of the lower layer in the double ignition sintering was markedly low. This is due to lowering of the maximum temperature and shortening of the high-temperature holding time in bed caused by the coke combustion under oxygen shortage. On the other hand, the low-temperature degradation (RDI) and the reducibility (RI) resulted in the same and suitable magnitudes between the two processes. Therefore, the improvement of sinter strength, especially in the lower layer, is the most important problem. Since the high coke content deteriorates the strength, the increase of bed height is recommended as a countermeasure.

In Fig. 12, the influence of bed height on sinter

Table 4. Comparison of calorific values and necessary amount of oxygen per material unit.

Materials	Calorific value (kcal/kg) (A)	Required O_2 (g· O_2 /kg) (B)	A/B	Remarks
Coke	5 710	1 920	3.0	FC: 85 % in coke Unreacted C: 10 %
Scale	680	130	5.2	M.Fe 21.2 % FeO 65.0 % } ...in scale Scale oxidized to Fe_3O_4
Limestone replaced with quick lime	430	0	—	Equivalent to CaO

Fig. 11. Comparison of sinter qualities in single ignition sintering and those in double ignition sintering.

Fig. 12. Influence of bed height on sinter strength (TI) in double ignition sintering (pot test)

strength is shown in comparison between the two sintering processes. In the case of a high coke content (4.0 wt%), the strength with the bed height of 1 000 mm in the double ignition sintering did not even reach that of the ordinary sintering with the bed height of 500 mm. In the case of a low coke content (3.4 wt%), the strength with the bed height of 750 mm in the double ignition sintering was nearly equal to that of the ordinary sintering with the bed height of 500 mm, though the absolute value of strength was low.

4. Effect of Oxygen Enrichment

Secondly, as another countermeasure, the oxygen enrichment by adding to air was discussed. The effect

of the oxygen enrichment on sinter strength was examined by the sinter pot test as shown in Fig. 13. The sinter strength in the upper layer in the double ignition sintering was nearly constant within the experimental range of oxygen content. On the other hand, the strength in the lower layer in the double ignition sintering was improved significantly together with the increase of oxygen content and reached to the same levels as those of the upper layer with 3 vol% of oxygen enrichment. Satisfactory *RDI* and *RI* were achieved. Thus, it is very effective to apply the oxygen enrichment to the double ignition sintering for the recovery of sinter strength because of the improvement of coke combustion.

Although many researches on the oxygen enrichment in sintering have been reported, the conclusive information on the sinter strength has not yet been obtained. The early reports differ in the effect of oxygen enrichment on the sinter strength: one¹⁵⁾ reported sinter strength was improved because of the expansion of heat pattern, while other³⁾ reported that it was deteriorated because of the unbalance between heat transfer and combustion. The difference between the two is also influenced by other sintering condition besides the oxygen content in air. In this experiment under the condition of relative shortage in oxygen, it is considered that the coke combustion and the sinter strength were improved by oxygen enrichment. The problem remains the subject of further study including energy saving.

3. Overall Evaluation in the Large DL-type Test Machine

In Fig. 14 the operation progress in the double ignition sintering with the actual sinter mix is shown for each layer. Both of the oxygen content and the temperature were measured in the bed as shown in the figure. In the early stage after ignition, the coke combustion in both layers simultaneously proceeded so that the oxygen content in the upper layer combusting gas became about 10 vol%, while that in the lower layer combusting gas almost zero. After the combustion in the upper layer was completed, the

oxygen content in the lower layer combusting gas recovered to about 10 vol%, because coke combustion in the lower layer occurred by induced air composition. However, the progress of coke combustion was slow because of the oxygen shortage. As a result, the temperature increased slowly and the maximum temperature remained mostly at 1200°C. Therefore, the strength in the lower layer could not be sufficient at such temperature level.

On the reflection of these results, the following experiment was carried out to maintain the oxygen content at a necessary oxygen level to keep good combustion; the air supply was increased by the high suction pressure of the fan. Moreover, the decrease of oxygen consumption and the increase of caloric supplement were tried by the use of the mill scale and the quick lime. Figure 15 compares the heat patterns immediately before BTP in the two sintering processes. The maximum temperature arose above 1250°C and reached a temperature level of the ordinary sintering process. However, it was considered that the sinter strength was not yet sufficient, because the holding time at high temperatures was half of that in the ordinary sintering.

In Table 5 the conditions and the results of the two comparative tests with the DL-type machine are shown. In the case of the double ignition sintering for the comparison 1, the conditions of low coke content and low suction pressure were selected for the reduction of energy consumption under a constant productivity. Coke combustion was performed under shortage of oxygen by the use of in-plant sinter mix. Therefore, the electricity was not reduced as much as expected and the coke ratio became worse than the ordinary sintering because of considerable deterioration of the sinter strength and sinter yield.

In the comparison 2 the possibility of high productivity in the double ignition sintering was considered with the adequate amount of oxygen supply and the compensation of heat. Consequently an extremely high productivity of 57 t/m² D and a slight reduction of energy consumption were accomplished because of

Blend: A
Coke content: 3.8%
Suction pressure: 11.8 kPa
Bed height: 500 mm (double ignition)

Fig. 13. Comparison of upper layer and lower one on *TI* in double ignition sintering with oxygen enrichment.

Fig. 14. Patterns of O₂ content in sintering gas and temperature in sintering bed in double ignition sintering for the comparison 1.

Fig. 15. Heat pattern in double ignition sintering for the comparison 2.

Table 5. Test results by DL test machine.

Process	Comparison 1		Comparison 2	
	Single	Double	Single	Double
Raw materials	In-plant mix		L*=1% L*=2% S*=0% S*=3% B*=0% B*=0%	
Coke ratio (%)	2.9	2.5	3.3	2.9
Suction (kPa)	8.3	11.0	15.4	19.0
Bed height (mm)	410	750	460	750
Return fine (%)	23.6	34.9	20.9	27.7
Productivity (t/d·m²)	25.4	25.3	36.0	56.9
TI (+10 mm)	62.4	54.3	66.0	54.6
RDI (-3 mm)	39.8	43.2	31.3	30.2
RI	72.2	74.0	67.4	72.2
Exhaust gas (Nm³/t)	1 888	1 161	1 480	843
Blower power (kWh/t)	9.7	7.8	14.1	9.9
Coke (kg/t)	43.7	45.4	47.8	46.5

* L: quick lime, S: scale, B: BF dust

the increase of sintering speed by the supply of the necessary oxygen amount. However, the considerable deterioration of the sinter strength was not improved: the sinter strength more than 60 is required in this test. Although both *RDI* and *RI* are satisfactory, the deterioration of the sinter strength is considered as a great drawback of the double ignition sintering.

In Fig. 16 the feasible limit is shown in consideration of both the coke content and the induced air flow rate by the use of the scheme similar to Fig. 8. The lower limit of oxygen content (10.5 vol%) necessary for combustion was restricted to the solid lines corresponding to the content of coke and mill scale in mix by the calculation from Figs. 5 and 10. The induced air more than the limits for the in-plant mix and the blend mix B' was required for the accomplishment

Fig. 16. Test condition of double ignition sintering in DL test machine.

Fig. 17. Supporting technologies for double ignition sintering.

of good sintering.

On the other hand, the regions feasible to ensure the sinter yield above 50 or 60 % are located at the right side of the dotted curves in the figure. As bordered by the two specific limits, namely one as the chemical limit of coke combustion and the other as the metallurgical limit of sinter bond, the region that satisfied both limits simultaneously was the feasible operation zone in the double ignition sintering. Consequently the condition of the double ignition in the comparison test 1 was far away from the feasible zone and was regarded as unsuccessful. On the other hand, the condition of the double ignition sintering in the comparison test 2 was in the feasible zone. However, this feasible zone was narrow and would not be present when a higher sinter yield more than 60 % is required. Therefore, it was considered extremely difficult to obtain satisfactory results for all aspects.

Finally on the basis of the investigation, the technological factors and their directions possible to realize the double ignition sintering were summarized as shown in Fig. 17.

IV. Conclusions

To confirm the lower limit of energy consumption in the actual sintering process, the experimental researches were carried out. Moreover on the basis of the results, the double ignition sintering in which oxygen in air is utilized efficiently was studied experimentally. The results obtained were summarized as follows:

(1) The lower limits of the induced air flow rate and the coke content in the actual sintering process were $9 \text{ Nm}^3/\text{m}^2 \text{ min}$ and $2.6 \text{ wt}\%$, respectively. These values were equivalent to the rates of about 5 kWh in electricity and about 30 kg in coke per ton sinter. Sinter productivity in this limit condition was calculated as about $12 \text{ t}/\text{m}^2 \text{ D}$.

(2) In the double ignition sintering, the adequate supply of oxygen and the maintenance of sinter strength were necessary. In this research, however, without oxygen enrichment the sinter productivity reached to about $57 \text{ t}/\text{m}^2 \text{ D}$ by the use of the high bed height and the high suction pressure when the sinter strength of 50 to 60 are allowable. In the future research, it is necessary to increase the sinter strength by improvement of the pre-treatment of sinter materials.

Nomenclature

A : reaction surface (m^2/m^3)
 C_g : specific heat of gas ($\text{kcal}/\text{kg } ^\circ\text{C}$)
 C_s : specific heat of solid ($\text{kcal}/\text{kg } ^\circ\text{C}$)
 d_c : radius of coke particle (m)
 f_c : reaction fraction of coke (—)
 G : mass velocity of gas (kg/min)
 h : heat transfer coefficient ($\text{kcal}/\text{m}^2 \text{ min } ^\circ\text{C}$)
 ΔH_c : combustion heat of coke (kcal/kg)
 ΔH_i : reaction heat of vaporization, decomposition and melting (kcal/kg)
 JPU : Japanese Permeability Unit ($= U \cdot (H/\Delta p)^{0.6}$) (—)
 K_c : overall reaction rate coefficient of coke (m/min)
 M : weight of raw materials (kg)

$[\text{O}_2]$: oxygen content (mol/cm^3)
 R_c : reaction rate of coke (mol/min)
 R_i : reaction rate of vaporization, decomposition and melting (mol/min)
 t : temperature of gas ($^\circ\text{C}$)
 T : temperature of solid ($^\circ\text{C}$)
 U : superficial velocity ($\text{Nm}^3/\text{m}^2 \text{ min}$)
 v : sintering speed (mm/min)
 W_c : coke weight per unit volume (kg/m^3)
 Z : distance in bed
 ε : void fraction (—)
 θ : time (min)
 μ_g : viscosity of gas ($\text{kg}/\text{m min}$)
 ρ_g : density of gas (kg/m^3)
 ρ_s : density of solid (kg/m^3)

REFERENCES

- 1) H. Wendeborn and F. Cappel: Agglomeration, Intersci. Publ., New York, (1962), 1041.
- 2) S. Nigo, J. Kimura, M. Ichimiya, S. Yasumoto, K. Nakajima and K. Kasahara: *Tetsu-to-Hagané*, **68** (1982), 2182.
- 3) E. W. Voice and R. Wild: *Iron Coal Trades Rev.*, **11** (1957), 841.
- 4) T. Yamagata, T. Futaguchi, Y. Hatakeyama, T. Kawasaki, G. Kochihira and M. Kato: *AIME Ironmaking Proc.*, **58** (1983), 99.
- 5) A. Tamei: *Japanese Patent Gazette*, **47** (1972), 26304.
- 6) K. Tashiro, H. Soma, J. Shibata, N. Konno and Y. Hosotani: *Tetsu-to-Hagané*, **66** (1980), 1603.
- 7) M. Yoshinaga, M. Ichidate, S. Sato, M. Kato and K. Yamamoto: *Tetsu-to-Hagané*, **67** (1981), S700; *Trans. Iron Steel Inst. Jpn.*, **22** (1982), B83.
- 8) I. Muchi and J. Higuchi: *Tetsu-to-Hagané*, **56** (1970), 371.
- 9) T. Hamada, T. Koitabashi and K. Okabe: *Tetsu-to-Hagané*, **58** (1972), 1567.
- 10) M. Yoshinaga and T. Kubo: *Sumitomo Search*, (1978), No. 20, 1.
- 11) A. L. Parker and H. C. Hottel: *Indust. Eng. Chem.*, **28** (1936), 1334.
- 12) S. Ergun: *Chem. Eng. Prog.*, **48** (1952), 918.
- 13) M. Sasaki and Y. Hida: *Tetsu-to-Hagané*, **68** (1982), 563.
- 14) T. Yamada, M. Fukutome, M. Okuyama, T. Kodama, Y. Imai, T. Hirai, K. Kitazawa and M. Haitani: *Tetsu-to-Hagané*, **63** (1977), S26.
- 15) E. Mazanek and M. Wyderko: *Stahl Eisen*, **89** (1969), 863.