KAWASAKI STEEL TECHNICAL REPORT
No.18 (May 1988)

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For the purpose of decreasing heat consumption of coke ovens, uniform carbonization in ovens and improvement of thermal efficiency in combustion chambers have been intended by controlling gas flow in flues and evaluating the state of carbonization. The experimental results show: (1) control of the flue slide brick opening area and elevation of top pressure are effective in uniform carbonization in the horizontal direction, and (2) elevation of combustion gas temperature is also found effective in improvement of heat efficiency. By application of the results, waste gas heat has been reduced due to improved thermal efficiency, and discharged coke temperature due to uniform temperature distribution. Through both the effects, heat consumption was decreased by about 40 kcal/kg-coal.

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1 Introduction

In the coke oven combustion control, it is very important to avoid over- and underheating of the coal which is charged into the coking chamber, and to maximize the efficiency of heat transfer from the combustion gas to the coal. Optimum conditions contribute greatly to ensured stability of coke oven operation and decreased heat consumption.

As a method of achieving uniform heating of coal, control techniques employing a coking-termination judging sensor and oven-temperature sensor have previously been reported concerning the coke oven.[1-3] However, techniques for clarifying the behavior of the gas flow in the flues, which compose individual combustion chambers, and for efficiently regulating coal heating, had not to date been established. Therefore Kawasaki Steel developed a simulation model for gas distribution[4] using a Carl Still coke oven and analyzed the behavior of gas flow in one of the combustion chambers and regenerators.[5-7] Further, in order to assess coal heating conditions, dust concentration during coke discharge was quantified, and using this dust concentration data, a method for evaluating the state of carbonization in a coking chamber was examined.[8] Through application of these results to commercial operation, it was possible to improve heat transfer in the combustion chambers and regenerators and to reduce the heat consumption in the coke oven by about 40 kcal/kg-coal.[9]

The present report describes this method for evaluating the extent of carbonization in a coking chamber, a method of regulating gas flow-rate distribution in a combustion chamber, and results of operational tests during M-gas (a mixed gas of blast furnace gas and coke

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oven gas) combustion, and further discusses gas flow-rate distribution and heat transfer distribution in the flues.

2 Method of Evaluation of Carbonization in a Coking Chamber

Whether heating conditions in a coking chamber are proper or not is ultimately evaluated by the carbonization of the discharged coke. Therefore, the authors examined the evaluation of carbonization in the coking chamber using the quantity of dust resulting from faulty carbonization at the time of discharge as a parameter.

2.1 System Outline

The outline of sensors installed on the coke guide car is shown in **Fig. 1**. Coke level, coke surface temperature, and the dust density of the coke passing through the guide at the time of discharge are measured continuously using a laser level meter, radiation pryrometer, and dust density meter. Carbonization is evaluated, as shown in **Fig. 2**, from coke surface temperature and dust density. In the figure, a coking chamber showing excess carbonization, one with insufficient carbonization, and one with uneven carbonization are found, and taking into consideration the distribution of charged coal, which is estimated from coke levels, this information is fed back to into the combustion adjustment and charging/leveling process.

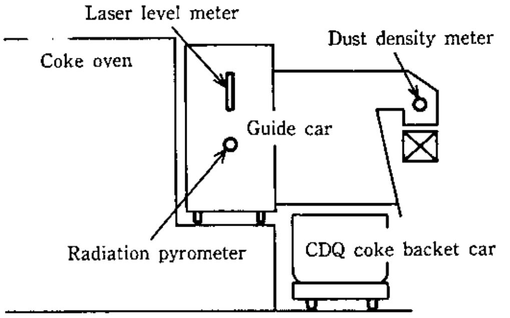

Fig. 1 Coke guide sensors

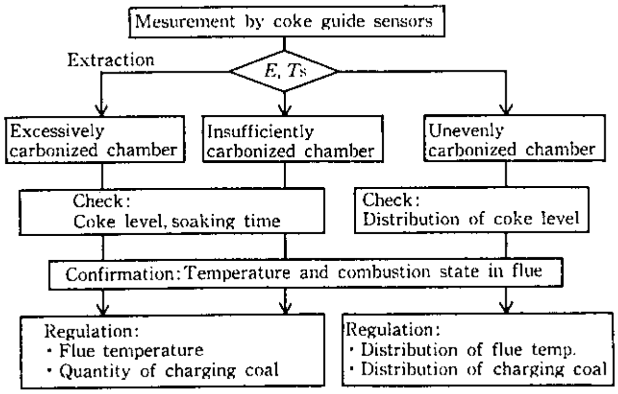

Fig. 2 Action flow based on evaluation of final coking state (E, index of dust concentration; T_S, discharged coke surface temperature)

2.2 Evaluation Index

Guide car dust density (C_t) at time t during coke discharge is given by the following Eq. (1) based on the Lambert-Beer Law:[10)]

$$C_t = A \log \frac{I_t}{I_0} \quad \cdots\cdots\cdots\cdots (1)$$

where I_0: Projected light intensity
I_t: Received light intensity at t
A: Constant (provided $A < 0$)

Therefore, the magnitude of total dust generation in the entire coking chamber at the time of coke discharge can be quantified using the index of dust concentration (E) defined by the following Eq. (2):

$$E = \left(\int_{t_0}^{t_1} C_t \, dt \right)^B = (\sum C_t)^B \quad \cdots\cdots\cdots (2)$$

where t_0: Coke discharge start time
t_1: Coke discharge end time
B: Constant

The relation between index E, the increase in H_2 concentration in coke dry quenching (CDQ) and soaking time is shown in **Fig. 3**. It is known that when insufficiently carbonized coke is charged into the CDQ unit, the concentration of H_2 in the CDQ circulating gas is increased by generated H_2 and that when combustion conditions are equal, the soaking time greatly affects the carbonization extent of discharged coke. Therefore, index E is considered a characteristic value expressing the carbonization extent of the discharged coke, and it can be seen that this value becomes smaller as the coke carbonization improves. Also, as shown in **Fig. 4**, there

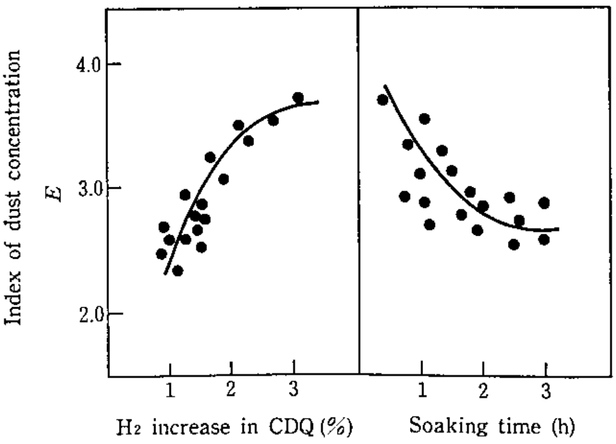

Fig. 3 Relationship between E, H_2 increase in CDQ, and soaking time

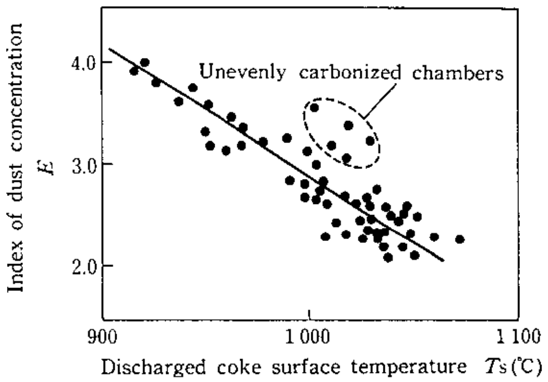

Fig. 4 Correlation between E and discharged coke surface temperature T_S

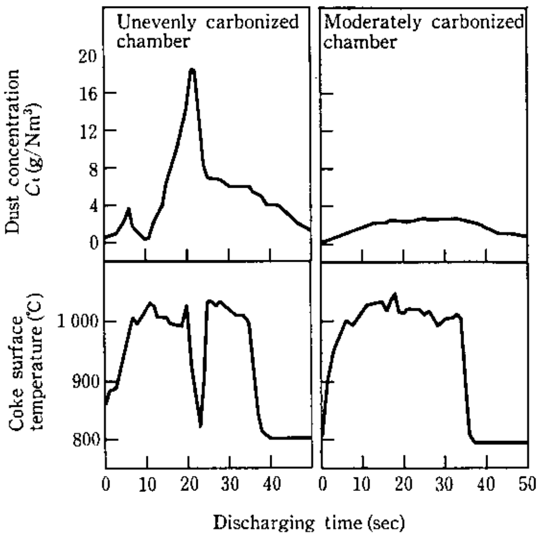

Fig. 5 Evaluation of carbonization distribution by using C_t and discharged coke surface temperature

is a definite negative correlation between index E and the average surface temperature of the discharged coke (T_S). In the coking chamber group indicated by a high index E deviating from the regression line, shown in Fig. 4, it was found that the coke surface temperature distribution in the chamber-length direction had developed into a regional trough, as shown in **Fig. 5**.

When index E is used to evaluate the drop in coke quality due to insufficient carbonization, a series of analytic/corrective processes becomes possible based on the relationship between T_S and index E shown in Fig. 4:

(1) T_S, which must be secured at the lowest level possible, can be determined.

(2) Coking chambers having a poor carbonization distribution in the chamber-length direction can be identified.

(3) T_S can be lowered by rectifying the distribution of discharged coke surface temperatures in the chamber-length direction.

In order to rectify the discharged coke surface temperature distribution in the chamber-length direction, it is necessary to adjust the gas flow-rate distribution in a combustion chamber, as this significantly affects the distribution of heat transferred from the combustion chamber to the coking chamber.

3 Method for Adjusting Gas Flow-rate Distribution in a Combustion Chamber

3.1 Control Factors for Gas Flow-rate Distribution

The channels of a combustion chamber and a regenerator in the Carl Still oven are exceedingly complicated. The flow of combustion air, M-gas, and combustion gas during M-gas combustion are shown in **Fig. 6.** When the channels of a combustion chamber and a regenerator are considered a piping network and the gas flow in the combustion chamber is assumed to be steady, the following Eqs. (3) to (8) are applicable to gas velocity (U), based on the mechanical energy balance of the fluid:[4]

$$\frac{P_{\text{out}} - P_{\text{in}}}{\rho} + \frac{U_{\text{out}}^2 - U_{\text{in}}^2}{2\alpha} + \frac{\rho - \rho_{\text{atm}}}{\rho} gZ + \sum H(U) = 0 \cdots\cdots (3)$$

$$H(U) = (K_1 + K_2 + K_3 + K_4)\frac{U^2}{2} \cdots\cdots (4)$$

$$K_1 = f_1(L, D, U) \cdots\cdots (5)$$

$$K_2 = f_2(S) \cdots\cdots (6)$$

$$K_3 = f_3(L, D, U) \cdots\cdots (7)$$

$$K_4 = f_4(S, U) \cdots\cdots (8)$$

where

$P_{\text{in}}, P_{\text{out}}$: Pressure at channel inlet and outlet (Pa)
ρ, ρ_{atm}: Density of combustion gas and air (kg/m^3)
$U, U_{\text{in}}, U_{\text{out}}$: Flow velocity of channels, channel inlet, and channel outlet (m/s)
g: Gravitational acceleration (m/s^2)
Z: Oven height (m)
H: Resistance loss of channel (m^2/s^2)
α: Flow velocity distribution compensation coefficient
L: Equivalent length (m)
D: Equivalent diameter (m)
S: Sectional area of channel (m^2)
K_1: Loss coefficient due to friction
K_2: Loss coefficient due to enlargement or contraction
K_3: Loss coefficient due to bending
K_4: Loss coefficient due to confluence or divergence

Equation (3) indicates that the distribution of gas flow

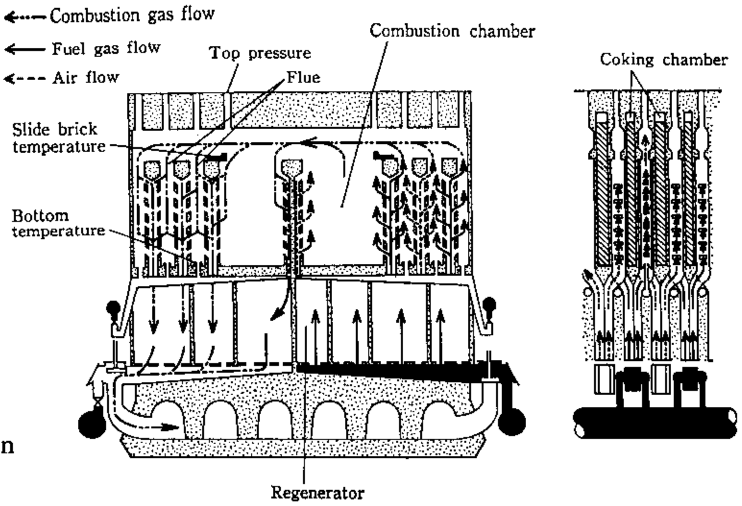

Fig. 6 Carl Still coke oven

rates to various channels can be controlled by pressure differentials between channel inlet and outlet, shown by the first term, the flow velocity at the channel inlet and outlet, shown by the second term, and the sum of resistance loss values in the various channels, shown in the fourth term. The third term in Eq. (3), which expresses buoyancy, is affected by combustion gas temperature which can be obtained from the result of gas flowrate distribution and by the preheating temperatures of the M-gas and air in the regenerator, but can be taken as a part of the first term if these temperatures are assumed to be equal in all flues.

3.2 Gas Flow-rate Distribution Adjustment Operation in Commercial Coke Oven

The presure difference between the channel inlet and outlet can be adjusted by controlling the air-slit opening area and exhaust valve draft pressure. Top gas pressure can be taken as an index of this adjustment. The velocity at the channel inlet and outlet can be adjusted using the combustion air flow rate and fuel gas flow rate, and these flow rates can be changed using the set values of the air ratio and fuel gas calorific value. The resistance loss of the channel can be adjusted by changing the area of the channel opening, since the resistance is a function of channel sectional area and flow velocity as shown in Eqs. (4) to (8) earlier. In actual operation, flue slide brick opening areas are adjusted by using the existing slide bricks.

4 Results of Operational Test

4.1 Adjustment of Flue Slide Brick Opening Area

The horizontal channel in the area above the combustion chamber is of the construction shown in **Fig. 7**, taking the coke side as an example. The slide brick opening areas of the No. 5 to No. 16 flues can be adjusted within the range shown in **Fig. 8**, but the opening areas of No. 1 to No. 4 flues cannot be changed.

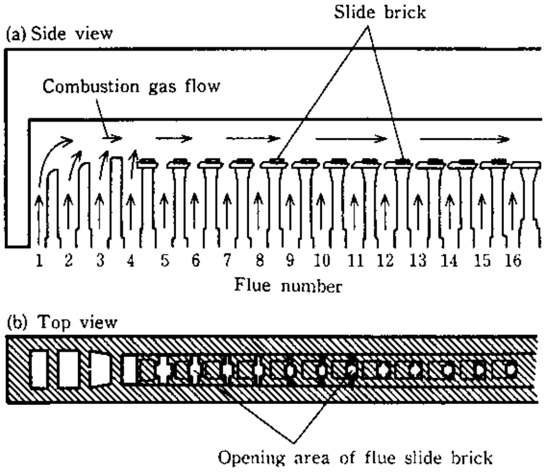

Fig. 7 Sections around the upper part of combustion chamber (coke side)

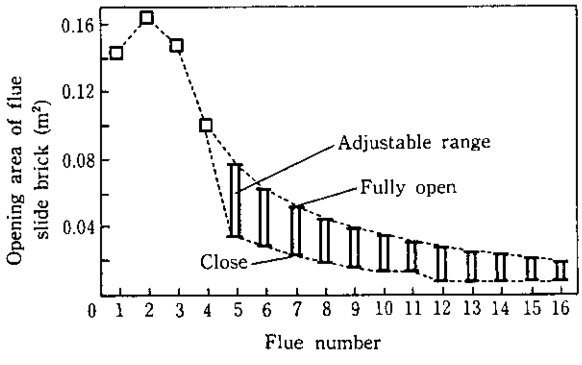

Fig. 8 Adjustable range of opening area on each flue slide brick (coke side)

To obtain the flue slide brick opening areas required to equalize heat transfer distribution in the chamber-length direction as much as possible, calculations were made using a gas distribution model[4)] based on Eqs. (3) to (8). An example of a calculated result for the opti-

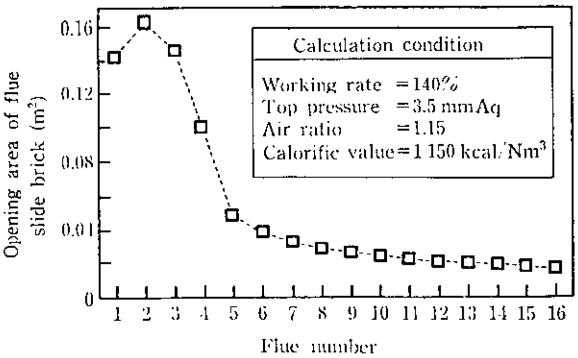

Fig. 9 Calculated optimum adjustment guidance of opening area on each flue slide brick (coke side)

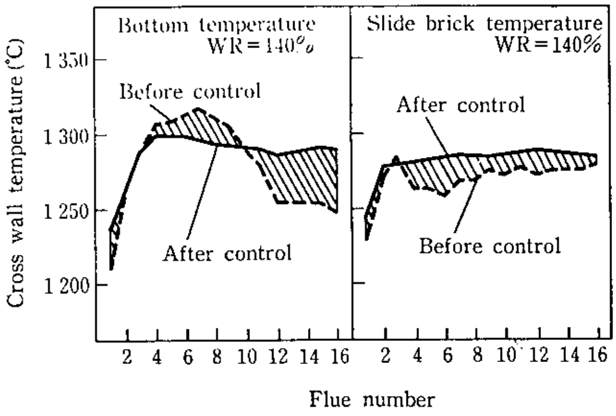

Fig. 10 Effect of flue opening area control on cross wall temperature profile (coke side)

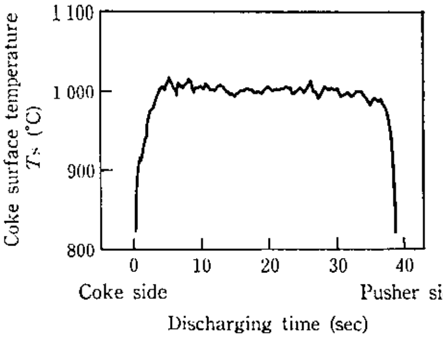

Fig. 11 Distribution of coke surface temperature after flue opening area control

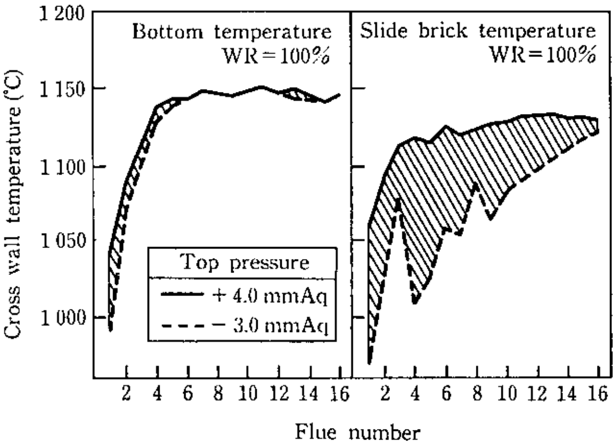

Fig. 12 Effect of top pressure control on cross wall temperature profile (coke side)

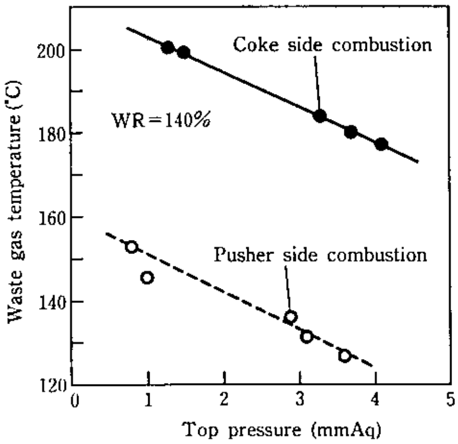

Fig. 13 Effect of top pressure control on waste gas temperature

mum flue slide brick opening areas on the coke side are shown in **Fig. 9**. By actually adjusting the flue slide brick opening areas of a commercial coke oven under the combustion conditions shown in Fig. 9 so that the opening areas would be as shown in Fig. 9, uniform temperature distribution in the chamber-length direction was obtained at the combustion chamber wall, except at the end flue, as shown in **Fig. 10**. Similarly, the discharged coke surface temperature also showed a uniform distribution, as shown in **Fig. 11**.

4.2 Adjustment of Top Pressure

The calculated result using a model indicated that the gas flow-rate distribution in flues would hardly change, even though the top pressure of the combustion chamber changed. In a brick-walled coke oven, however, brick joints and cracks act as unwanted air passages, and the effect of air thus entering the oven must be considered.

When top pressure is elevated while the flue slide brick opening area, the M-gas, and air ratio are constant, combustion chamber wall temperature distribution in the chamber-length direction changed as shown in **Fig. 12**. The elevation of top pressure raised the wall temperature of the combustion chamber at the end flue, improving carbonization there. In addition, the elevation of top pressure resulted in a lowering of the waste gas temperature and in a decrease in waste gas heat loss, as shown in **Fig. 13**. These results are considered attributable to the reduction in air entry into the oven, making it possible to optimize gas distributions in the combustion chamber and regenerator.

4.3 Adjustments of M-gas Calorific Value and Air Ratio

When the set values for M-gas calorific value and air ratio are changed to increase or decrease the flow rates of the M-gas, air, and combustion gas which flow through the combustion chamber, the combustion gas temperature changes and the efficiency of heat transfer from the combustion gas to the wall surface of the combustion chamber are affected. Accordingly, these effects were examined under the combustion conditions in **Table 1**.

Table 1 Experimental conditions

	Condition I*1	Condition II*2
Working rate	140*3 %	
Heat consumption	580*3 kcal/kg-coal ($\sigma=5.1$)	
Total water of coal	9.3*3 % ($\sigma=0.34$)	
Top pressure	3.5*3 mmAq ($\sigma=0.3$)	
Opening area of each flue	The optimum*3	
Air ratio	1.30	1.10
M-gas calorific value	920 kcal/Nm^3	1 150 kcal/Nm^3

Note *1 Condition which minimize the combustion gas temperature T_F

*2 Condition which maximize the combustion gas temperature T_F

*3 Constant value

4.3.1 Thermal Efficiency of Entire Coking Chamber

As a typical value showing changes in the combustion gas temperature in the flues, the adiabatic flame temperature (T_F) for an ideal combustion process given by the following Eq. (9) was used:

$$T_F = \frac{H_l + G_W \Delta h}{G_W \bar{C}_P} \quad \cdots\cdots\cdots\cdots\cdots\cdots (9)$$

where H_l: Lower calorific value of fuel gas (kcal/kg-fuel)

G_W: Amount of wet combustion gas (kcal/kg-fuel)

Δh: Air and fuel gas preheating enthalpy given by regenerator (kcal/kg)

$\bar{C}_P$: Average specific heat of combustion gas (kcal/kg · °C)

In a commercial coke oven operated with constant heat input, working rate, and moisture value of charged coal, T_F was changed by controlling the air ratio and M-gas calorific value within the ranges shown in the Table 1. As a result, it was observed, as shown in **Fig. 14**, that as T_F rises, net coking time (θ) is shortened and index E decreases, improving the overall carbonization state of the coking chamber and facilitating heat transfer from the combustion chamber to the coking chamber. In addition, as the air ratio is lowered and the M-gas calorific value is increased, T_F rises.

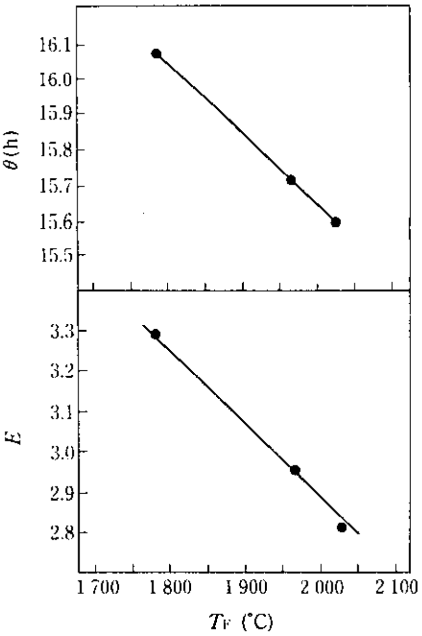

Fig. 14 Effect of adiabatic flame temperature for ideal combustion process, T_F, on net coking time θ and index of dust concentration E

4.3.2 Heat Transfer Distribution in Coking Chamber

The relation between T_F, the average temperature of the combustion chamber wall surface (T_W) and end flue wall temperature (T_E) are shown in **Fig. 15**. As T_F rises, T_W and T_E also rise; however, since $(\Delta T_W/\Delta T_F) > (\Delta T_E/\Delta T_F)$, as T_F rises, the value of $(T_W - T_E)$, namely, the difference between the end flue wall temperature and the average cross wall temperature, also increases. However, the rise in T_F improves the carbonization state of the entire coking chamber, as mentioned in Sec. 4.3.1. Therefore it is necessary, when determining combustion conditions which will improve coke heat consumption performance, to consider T_F, which affects the heat transfer efficiency of the entire coking chamber, in addition to the combustion chamber temperature distribution[11] which has to date been used as an operating guideline.

4.4 Effect of Reduction of Coke Oven Heat Consumption

The following were results of the effort to optimize

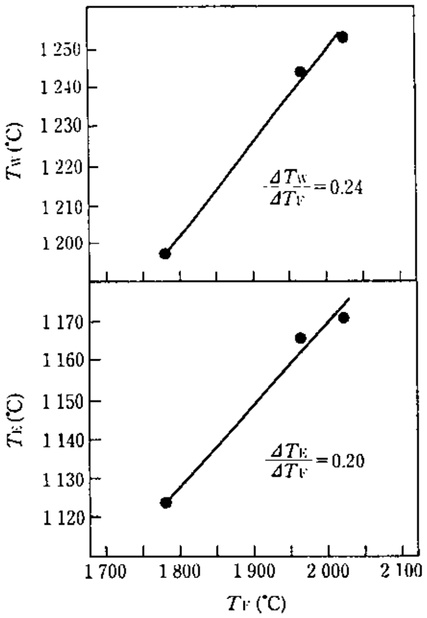

Fig. 15 Relationship between T_F, T_E and T_W (T_E, end flue wall temperature; T_W, average cross wall temperature)

combustion conditions, based on the findings described in Sec. 4.1 to 4.3:

(1) Through the adjustment of the flue slide brick opening area and elevation of top pressure, the gas flow-rate distribution in the flues was optimized, resulting in a lowering of the waste gas temperature and discharged coke surface average temperature by 37°C and about 20°C respectively.

(2) Through an increase in M-gas calorific value and a lowering of the air ratio, the efficiency of heat transfer from the combustion gas to the coking chamber wall was improved, resulting in a lowering of the waste gas flow rate by about 21%.

Application of combustion adjustment to the coke oven at Mizushima Works resulted in a lowering of carbonization heat consumption of about 40 kcal/kg-coal, and more generally in the establishment of a technique which can, in combination with the energy savings effects of other techniques, achieves a reduction in carbonization heat consumption of about 70 kcal/kg-coal. As shown in **Fig. 16**, coke oven operation can now be conducted at a carbonization heat consumption of less than 560 kcal/kg-coal.

5 Discussion

5.1 Gas Flow-rate Distribution for Equalizing Heat Transfer Distribution in Chamber-Length Direction

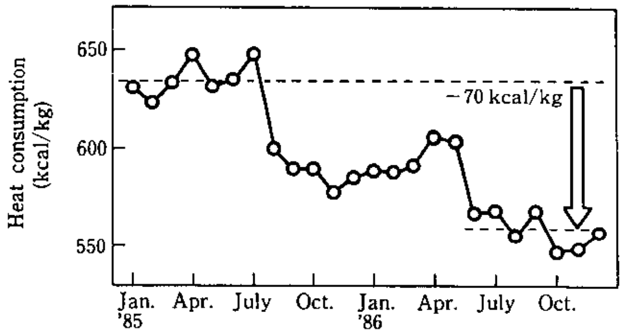

Fig. 16 Transition of heat consumption of coke ovens in Mizushima Works

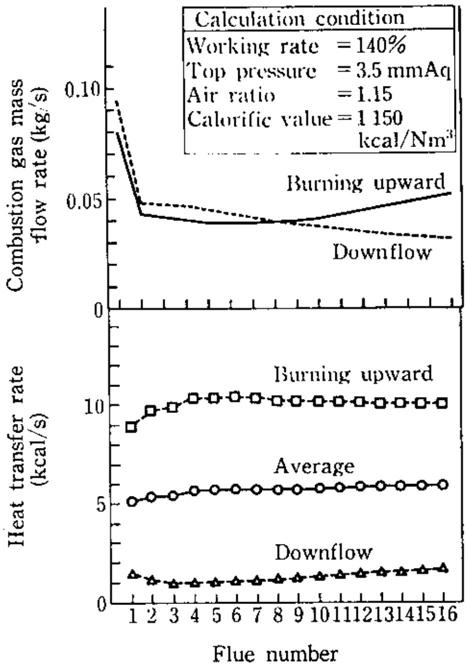

Fig. 17 Calculation results of combustion gas distribution and heat transfer rate on each flue (coke side)

The following conclusions were reached regarding flue slide brick opening area (Fig. 9), based on the gas flow-rate distribution in the flues and heat transfer distribution (**Fig. 17**) from the combustion gas to the coking chamber wall, as calculated from the gas distribution model:

(1) More combustion gas is distributed to the end flue than to other flues, both when fuel gas burns upward and when combustion gas flows down, and this volume reached more than 10% of the total combustion gas.

(2) A gas flow which will equalize heat transfer distribution from the combustion gas to the coking chamber wall has a tendency to become a central flow when fuel gas burns upward and a peripheral flow

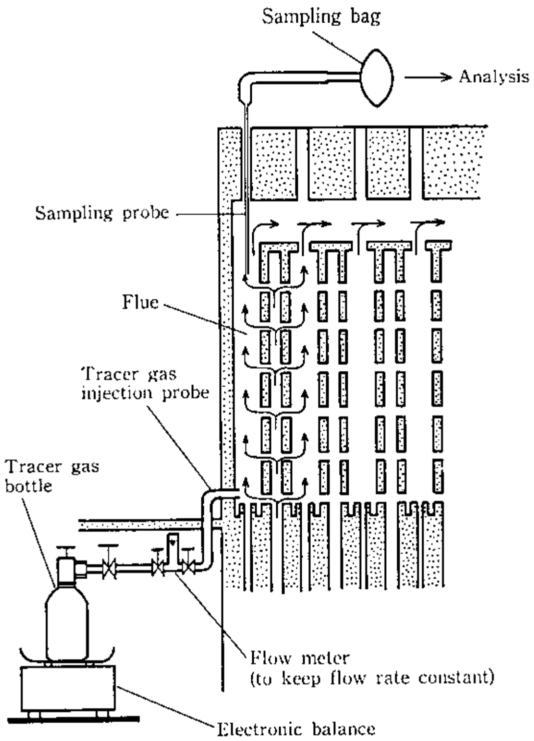

Fig. 18 Measurement of end flue gas flow rate

Table 2 Combustion gas distribution of end flue

	Measured value		Calculated value	
Top pressure (mmAq)	Combustion gas flow rate (Nm^3/min)	Distribution factor (%)	Combustion gas flow rate (Nm^3/min)	Distribution factor (%)
−3.0	2.3	10.1	2.5	10.9
+4.0	2.5	10.9		

when combustion gas flows down.

Item (1) is attributable to greater flow rates of M-gas and air, which are distributed through separate channels of the M-gas and combustion air installed at the end flue of the Carl Still oven.

The combustion gas flow rate was measured using the flow rate measurement method using tracer gas[12] when combustion gas burnt upward in the coke side flues (**Fig. 18**). The results are shown in **Table 2**. The measured value and the calculated results show good agreement, indicating the validity of the calculation mentioned in (1). Even though more combustion gas is distributed to the end flue, the wall temperature at the end flue is lower than that of other flues, because, as shown in Fig. 17, the degree of heat transfer from the combustion gas to the coking chamber wall at the end flue is less than at other flues, and a greater degree of heat is lost through radiation from the oven body.

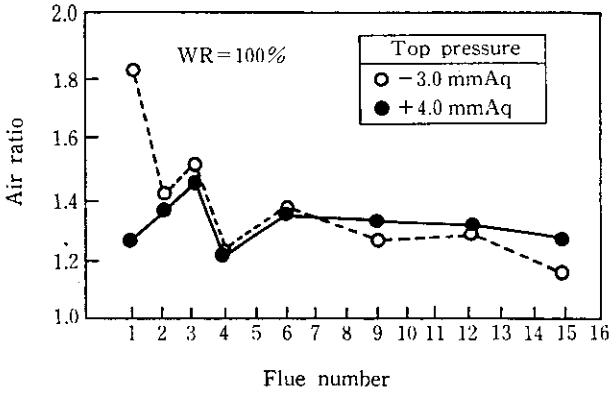

Fig. 19 Measurement results of air ratio on each flue (coke side)

Table 2 indicates that even if top pressure is changed, changes in the gas flow-rate distribution at the end flue will be minimal. From this, it is presumed that the reason the end flue combustion chamber wall temperature dropped when the top pressure was lowered is because the M-gas distribution to the end flue had lost the equilibrium indicated in Eq. (3) and become a central flow due to air entering the coke oven in the manner described in Sec. 4.2. This phenomenon can be confirmed from the fact that the lowering of top pressure caused the O_2 concentration to rise at the end flue and to drop at the center flue, as seen in the air ratio distribution in the flues, shown in **Fig. 19**, measured for top pressures of −3.0 mm Aq and +4.0 mm Aq.

The reason for the different gas distribution trends in flues when fuel gas burns upward and when combustion gas flows down is considered to be the fact that the direction of the gas flow when fuel gas burns upward and when combustion gas flows down is reversed, as shown in Fig. 6, and f_2 and f_4 of K_2 and K_4 respectively in Eq. (4) changed, changing the equilibrium of resistance losses in the flues. From such gas distribution trends, it can be seen that the ratio of heat input due to preheating in the regenerator at the periphery of the coke oven is higher than that at the oven center.

5.2 Changes in Thermal Efficiency Due to Combustion Conditions

The heat transfer distribution in the flues was calculated using a model for a case, when the air ratio is lowered from 1.30 to 1.10 and the M-gas calorific value is raised from 920 kcal/Nm^3 to 1 150 Kcal/Nm^3 with the flue slide brick opening areas, heat input, and top pressure constant. The results are shown in **Fig. 20**, which indicates the following:

(1) The efficiency of heat transfer from the combustion gas to the coking chamber wall surface is improved by about 5%.

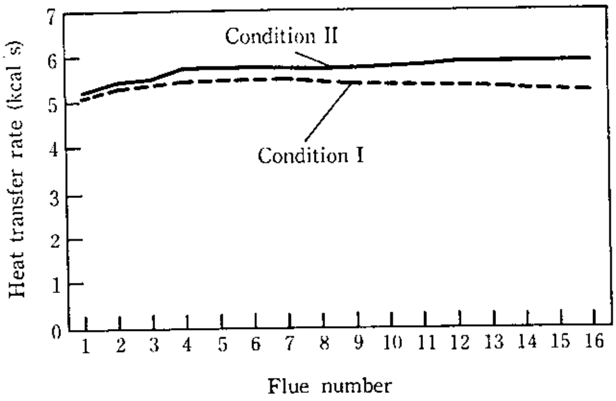

Fig. 20 Calculated effect of burning condition on heat transfer rate (coke side)

(2) The quantity of heat transferred from the combustion gas to the coking chamber wall surface at the end flue increases, but the ratio of increase is smaller than the average increase for all flues.

(3) The heat transfer distribution at the oven center is comparatively improved.

Items (1) and (2) agree with the the operational results of commercial oven described in Sec. 4.3 (Figs. 14 and 15), indicating that thermal efficiency is improved by lowering the air ratio and increasing the M-gas calorific value. Item (3) is considered a result of changes in thermal efficiency at the regenerator due to changes in the quantity of combustion gas. Based on the ratio of decrease in net coking time shown in Fig. 14, however, the improvement in actual thermal efficiency is estimated at about 3%, a smaller figure than the calculated result shown in Item (1). This matter requires future examination.

6 Conclusions

With the aim of decreasing coke oven heat consumption, a method for evaluating the state of carbonization in a coking chamber was examined. An attempt was also made to make carbonization uniform in the respective coking chambers and to improve efficiency of heat transfer in the respective combustion chambers by controlling the gas flow rate distribution in the flues. The following results were obtained:

(1) As an index for evaluating the extent of carbonization, index E was proposed; this index quantified dust density at the time of coke discharge, and its usefulness was confirmed.

(2) To make carbonization uniform in the chamber-length direction, proper control of the gas flow-rate distribution in the flues was found effective, and a technique was established to control gas flow-rate distribution using the slide bricks and top pressure.

(3) It was confirmed that in order to improve efficiency of heat transfer in the combustion chamber, raising the flame temperature with lowering the air ratio and raising M-gas calorific value were important and effective in achieving an optimal combustion process.

(4) After analysing gas flow in the flues, it was found that the end flue receives 10% or more of the total combustion gas, and that gas distribution in the flues has a tendency to become a central flow when gas burns upward and a peripheral flow when combustion gas flows down.

(5) Following the application of the findings described above to all coke ovens at Mizushima Works, operation with a monthly average coke-oven heat consumption of 560 kcal/kg-coal or below has been maintained since July 1986.

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