Development and Improvement of the Measuring Methods for the Computer Control of Blast Furnace*

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Synopsis

For the successful control of the hot metal temperature of the blast furnace, it is necessary to measure accurately the operational data such as blast conditions, charge conditions, and top gas compositions which are to be input to the control model. By the use of the mathematical simulation model of the blast furnace, the required accuracies of measurements for the control of the hot metal temperature are investigated. It was found that the measurement accuracies of the N_2 content and the CO_2 content of the top gas, the Fe content of burden and the blast flow rate were not enough.

The followings were carried out in order to improve the accuracies of the calculations of the material and heat balances and the accuracies of the prediction of hot metal temperature.

- 1) Development of the highly accurate gas-chromatography
- 2) Development of the sinter property tracking system
- 3) Check of the measurement accuracy of the blast flow rate
- 4) Improvement of the measurement timing of the hot metal temperature

Owing to these improvements, the automatic computer control system of the hot metal temperature could be applied to Kokura No. 2 BF for 2.5 years until the blow out of the furnace and this system had contributed to the stable and low cost operations.

I. Introduction

The computer control system of the thermal condition in the blast furnace have been studied for more than ten years by many investigators and various systems have been developed. However, it would seem that there are few cases in which the automatic control systems of the hot metal temperature are in practical applications over a long period. The reason why the automatic control system of the blast furnace was unsuccessful in use were due to not only the problem of exactness of the simulation models but also the uncertainty of the operational data which were to be input to the model.

After the study of a general control scheme, the authors have developed a simplified mathematical simulation model of the blast furnace process and an advanced automatic control system of the hot metal temperature. For the more severe control of the hot metal temperature, the more accurate measurements are required. From this view point, the required accuracies of the operational data which were necessary to estimate the hot metal temperature within $\pm 5^\circ C$ were investigated and compared with their actual accuracies.

As a result, it has been found that the measurement accuracy of Fe content of charged material, N_2 and CO_2 contents of the top gas, and blast flow rate are not sufficient. Then, some improvements for these mea-

surements were carried out and the accurate measuring devices or methods were developed. In the present paper, the study on the measurement accuracy, the improvements in the measurements and their application results to the commercial blast furnace are described.

II. Accuracy of Measurement Required for Control of the Hot Metal Temperature

1. The Mathematical Simulation Model of the Blast Furnace

The detail structures of the control model^[1,2] were already reported. In the present paper the outline of the model is briefly described.

1. Assumptions for the Model

The simulation model of the blast furnace is based on the following assumptions.

(1) There exist no radial distributions of state variables in the furnace.

(2) Reaction regions in the furnace are divided into five vertical zones and only the specified reactions take place in each zone. (Fig. 1(c))

(3) The resident materials in each zone remain constant (Fig. 1(b)). Therefore the ore is charged according to the production rate of the hot metal and the coke is charged according to its consumption rate in the furnace.

(4) The material balance is calculated for each chemical component of solid and gas, while heat balance is calculated in each zone by the use of average solid temperatures (TS_i , $i=1\sim 5$) and average gas temperatures (TG_i , $i=1\sim 5$). (Fig. 1(a))

2. Simulation of the Blast Furnace Process by the Model

As is shown schematically in Fig. 2, the blast furnace process is simulated by the three steps, such as the calculations of the reaction rate, the material transfer and the heat transfer.

(1) Calculation of the Reaction Rates

As shown in Fig. 1, ten kinds of reaction rates ($R_1\sim R_{10}$) are taken into consideration in this model. However, for the prediction of these reaction rates, it is necessary to formulate the two reaction rates into the predictive form, namely, the carbon solution loss reaction rate (R_4) and the iron production rate (R_5).

In Fig. 3, the step response characteristics of the reaction rates, R_4 and R_5 , are illustrated. The changes in these rates (R_4 , R_5) can be predicted on the basis

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Fig. 1. Structure of the blast furnace model.

Fig. 3. Step responses of reaction rates and hot metal temperature to main operating variables.

of their step response characteristics to the operational variables. The predicted reaction rates (R_4 , R_5) should be adaptively modified by the observed values because these reaction rates also change by the unknown factors. Thus the prediction equations of these reaction rates (R_4 , R_5) can be formulated as follows.

$$R_5^c(n) = \sum_{k=-\infty}^n \sum_{i=-\infty}^n g_k(n-i) U_k(i) \Delta t + \delta R_5^c(n) \dots \dots \dots (1)$$

$(R_4^c(n): \text{similar to } R_5^c(n))$

where,

$$\delta R_5^c(n) = \delta R_5^c(n-1) + \alpha_{R_5} (R_5^{ob}(n-1) - R_5^c(n-1)) \dots \dots \dots (2)$$

$$R_5^{ob} = \frac{1}{R_{O/Fe}} \left(2(CO_2)_0 + (CO)_0 - 2(O_2)_5 \right) + \frac{P_{oilH}}{2} (Oil)_5 - (H_2)_0 \dots \dots \dots (3)$$

- R_5^c : predicted value of the iron production rate
- R_5^{ob} : observed value of the iron production rate
- U_k : operational variable

Fig. 2. Forward simulation of blast furnace process by the mathematical model.

- g_k : impulse response function of the iron production rate to operational variable U_k (which is derived from its step response characteristics as shown in Fig. 3)
- δR_5 : adaptive feedback term
- α_{R_5} : feedback gain
- Δt : time interval of computation
- n, i : time index (ex., n means the time of $n\Delta t$)
- $R_{O/Fe}$: oxygen to iron rate in charged iron ore
- $(X)_0, (X)_5$: flow rate of material X outgoing from furnace top or flown into furnace
- P_{oilH} : hydrogen content rate in heavy oil.

Furthermore, the reduction rate (R_9) by hydrogen is predicted from the hydrogen concentration in the bosh gas, and also adaptively modified by the observed value. The reaction rates (R_6 , R_7 , R_8) concerning the combustion in front of the tuyeres are determined immediately from the blast conditions. The other reaction rates (R_1 , R_3 , R_{10}) can be predicted under the assumption (3) as the functions of the iron production rate (R_5) and the reduction rate (R_9) by hydrogen.

(2) Calculation of the Material Transfer

The flow rate of the material transferred to the next zone is calculated on the basis of the predicted reaction rates such that the amount flown out is equal to the sum (difference) of the amount flown in and the amount generated (disappeared) by the reactions.

(3) Calculation of the Heat Transfer

The temperatures of solid and gas at each zone are calculated from the heat balance equations set up for solid and gas at each zone. In the heat balance equations, the heat flown in and flown out through the material transfer, the heat of reaction, the heat exchange between solid and gas and the heat loss through the furnace wall are considered.

Figure 4 shows examples of calculated stationary temperature of each zone and dynamic transitions of solid temperature of the fifth zone.

2. Required Accuracy of Measurement

For the successful control of the hot metal temperature by the use of present simulation model, it is necessary to measure accurately the operational data such as blast conditions, charge conditions, and the top gas compositions.

In order to study the required accuracy for the measurements the allowable errors of measurement on each datum, which correspond to 0.5 % of the iron production rate and to 5 °C of the hot metal temperature, were calculated and compared with the actual measurement accuracy of the instruments conventionally used in the blast furnace operations. These sensitivity analysis are carried out by the use of Eqs. (1) to (3) and so on. For example, the influence of the change of the operational variable (U_k) on the iron production rate (R_5^i) is calculated numerically by the use of Eq. (1), where in Eq. (1) $\partial R_5^i(n)$ is equal to zero. Similar to the above method, the influence of the measurement accuracy of CO₂ in top gas on the iron production rate is calculated numerically by the use of Eqs. (3), (2), (1), where the CO₂ content is only changed and the others are constant.

The influences on the hot metal temperature are similarly calculated by the use of the carbon solution loss reaction rate (R_4) and the iron production rate (R_5). The results are shown in Table 1. It has become clear that the measurement accuracy of the Fe content of charged material, and the N₂ and CO₂

contents of top gas are not sufficient for the calculation of both material and heat balances. Although the measurement of the blast flow rate is accurate enough for heat balance, it is not adequate for material balance. From these sensitivity analysis, the high accuracy gas-chromatography has been developed and the other measurement methods of blast conditions has been improved.

III. Improvement of Measurement Accuracy

1. Development of Accurate On-line Gas Analysis

For the control of the hot metal temperature within ±5 °C of target value, the accuracy of the top gas composition analysis should be within ±0.11 % for N₂ and ±0.08 % for CO₂ as shown in Table 1. For the highly accurate analysis, it is necessary to maintain a gas-analyzer in more sensitive and stable conditions. And also the sample gas has to be representative of blast furnace condition, and a highly accurate standard gases for calibration are necessary.

1. Development of High Accuracy Gas-chromatography³⁾

A gas-chromatography is usually adopted for the on-line analysis of top gas composition. From the investigation it has been made clear which factors will disturb the stability and accuracy of on-line gas-chromatography. The experimental results are shown in Table 2. The factors which influence largely on the stability and accuracy of analysis are as follows; 1) the kind of carrier gas, 2) temperature fluctuations of columns and detector, 3) the stability and the accuracy of signal processing units.

In order to develop the highly accurate gas-chromatography, several improvements have been carried out which are also shown in Table 2. The main improvements are as follows.

(1) Carrier gas is changed from Ar to He in order to increase the sensitivity of thermal conductivity detector (T.C.D.).

(2) Isothermal vessels are duplicated, and columns and T.C.D. are put in the inner isothermal

Fig. 4. Calculation of the temperature in the furnace by the simulation model.

Table 1. Comparison between measuring accuracy required for the control of hot metal temperature and conventional blast furnace operation.

		Fe content in charged material* (%)	Blast volume* (%)	Top gas composition (%)			
				N ₂	CO	CO ₂	H ₂
Measuring accuracy required for control (Estimation from model)	Allowable error corresponding to 0.5 % of iron production rate	0.35	0.375	0.15	0.18	0.09	0.18
	Allowable error corresponding to 5° C of hot metal temperature	0.36	3.75	0.11	0.10	0.08	0.32
Measuring accuracy maintained for usual operation		0.50	0.50	0.50	0.15	0.15	0.05

Note :

- 1) * mark indicates relative value. Others indicate absolute value. (± sign is neglected.)
- 2) The accuracy of measuring Fe content in the charge material, N₂ and CO₂ in the top gas are not enough. The blast volume is accurate for heat balance, while not for mass balance.

Table 2. Factors influencing the stability of analysis of gas-chromatography and their improvements.

Factor	Influence on the analysis of conventional gas-chromatography	Improvement of new gas-chromatography
1. Analyzer		
a) Carrier gas	The sensitivity of T.C.D. He>Ar	He-gas is adopted for carrier gas
b) Temperature fluctuation in isothermal vessel	0.33 vol% /1 °C	Duplicate isothermal vessels are adopted and its temperature controlled within ±0.05 °C
2. Ambient temperature fluctuation	0.28 vol% /10 °C	Signal-processing units are replaced with μ -CPU
3. Atmospheric pressure fluctuation	0.30 vol% /10 mm bar	Adoption of total sum compensation method
4. Power supply voltage fluctuation	+0.15 vol% /20 V	Stabilization of the T.C.D. power supply and adoption of digital signal-processing units
5. fluctuation of vapor in sample gas	-0.05 vol% /1 °C (dew point)	Adoption of total sum compensation method
6. Improvement of the accuracy of signal processing units		Adoption of digital type signal-processing units

vessel in order to keep their temperature fluctuation within ± 0.05 °C.

(3) A micro-computer is adopted and T.C.D. signal are directly converted to digital data, and gas compositions are calculated with high accuracy from these data. Automatic calibrations and self-check are also carried out by micro-computer. The mole amount of sampled gas is affected by the changes in the atmospheric pressure and the dew point of the gas. However, these two influences can be compensated by calculating the ratio of each component to the summation of total components, namely total-sum compensation method. Owing to these improvements, the new gas-chromatography has attained sensitive analysis with high stability. As shown in Fig. 5, the stability of the N₂ analysis is ± 0.02 % and that of the CO₂ analysis is ± 0.02 % in 8 hr.

2. A Standard Gas for Accurate Calibration of the Analyzer

For the analysis of the top gas compositions within ± 0.1 % accuracy, the gas-analyzer must be calibrated by the standard gases of which compositions were determined with the uncertainties less than ± 0.1 %. The conventional standard gas of which compositions are determined by the volumetric method cannot be used for a highly accurate analysis, because the measurement of the volume of each component have the uncertainties of the order of ± 0.5 %. The primary

Fig. 5. Stability of high accuracy gas-chromatography checked by standard gas.

Table 3. Effect of errors in composition of conventional standard gas on the calculation of model.

Gas components	Stability of analysis	Error in composition of conventional standard gas* (%)	Effect of the composition errors on the calculated iron production rate	
	Standard deviation (%)		Sensitivity**	Error of iron production rate (%)
H ₂	0.01	0.04	-2.78	-0.11
N ₂	0.05	-0.44	-3.33	1.46
CO	0.03	0.26	2.77	0.72
OC ₂	0.03	0.13	5.55	0.72
Total effect on iron production rate				2.79

* Checked by primary standard gas
** Percentage increment of iron production rate per 1 % increment of gas component

standard gases of which compositions are determined by the weight methods have the high accuracy, because the measurement of weight by an analytical balance has the accuracy of ± 0.001 %. The conventional standard gas for the on-line gas-analyzer was checked by a primary standard gas and the influence of the composition error on the estimated iron production rate was calculated. The results are shown in Table 3. It shows the deviation about 2.8 % between the calculated iron production rate and the actual one. This deviation has been arisen from the error of compositions of the conventional standard gas. The primary standard gas should be used for the high accuracy calibration.

3. Influence of Gas Cleaning on Gas Composition

The top gas is cleaned by various types of gas cleaning equipments such as dust catcher (D.C.), venturi-scrubber (V.S.) and electric type precipitator (E.P.). It is easy to maintain the gas sampling probe at the down stream of V.S. or E.P.; however, the CO₂ gas was absorbed when it was cleaned by water. The compositions of the gas sampled from V.S. outlet was compared with those from D.C. outlet. The CO₂ content of the gas through V.S. is 0.16 % lower than that through D.C., and the N₂ content of the gas

Fig. 6. Influence of the CO₂ absorption by water on the calculated iron production rate.

through V.S. is higher than that through D.C. as shown in Fig. 6. These are the results of the absorption of CO₂ by water. In order to analyze the gas composition within 0.1 % accuracy, the sample gas should be sampled before it is cleaned by water.

4. The Application of High Accuracy Gas-analysis

The hot metal temperature control systems with these new analytical methods are tested at the blast furnace in commercial operations. The results are shown in Fig. 7.

By the use of the high accuracy gas-chromatography, the estimated temperature which are calculated from the simulation model have agreed well with the actual hot metal temperatures.

2. Improvements of the Other Measurements

1. Improvements of Measurement Accuracy of Chemical Components of Raw Materials

The weights of the raw materials charged into the blast furnace are measured by loadcells with good accuracy of $\pm 0.2\%$. On the other hand, the chemical components of the raw materials were analyzed with long sampling interval, and therefore the representability of the measured values was not so sufficient. In order to increase the sampling and analyzing frequency of the sinter which occupies the most part of the ore, an automatic sampler and analyzer were adopted and the frequency of analyses was increased from once every 8 hr to once every hour. Furthermore, as shown in Fig. 8, the sinter tracking system which tracks the data of the sinter properties from the sampling point to the blast furnace through many bins, was developed. The contributions of these improvements are as follows:

(1) Improvement of Accuracy of Material Balance

Figure 9 shows that by the increase of the sampling frequency and the adoption of the sinter tracking system the difference between the actual amounts of tapped hot metal and the amounts of charged iron was decreased from ± 3 to $\pm 2\%$. The $\pm 2\%$ difference is rather large, but it seems to be acceptable because the iron residue amount in the blast furnace fluctuates so much.

In the same way the difference between the actual

	Test period	Errors of analysis (%)	Hit ratio of hot metal temperature estimation* (%)
High accuracy gas-chromatography	21 days	N ₂ ≤ 0.06 CO ≤ 0.03 CO ₂ ≤ 0.03	82.3 (95.1)
Conventional gas-chromatography	21 days	N ₂ ≤ 0.3 CO ≤ 0.15 CO ₂ ≤ 0.15	78.6 (94.6)

* Temperature within $\pm 10^\circ\text{C}$, or (within $\pm 15^\circ\text{C}$)
The number of taps of which temperature coincide with target
Hit ratio = $\frac{\text{The number of taps of which temperature coincide with target}}{\text{The total number of taps}}$

Fig. 7. Effect of the accuracy of top gas analysis on the estimation of hot metal temperature.

Fig. 8. The data tracking system of sinter properties.

Fig. 9. The improvement in the accuracy of calculated hot metal production.

basicity of slag and the basicity calculated from material components was decreased from ± 5 to $\pm 2\%$ as shown in Fig. 10.

(2) Improvement of Prediction Accuracy of Hot Metal Temperature

The change in the Fe content of the sinter affects the hot metal temperature through the change in the coke ratio. Figure 11 shows an example of the con-

Fig. 10. The improvement in the accuracy of calculated CaO/SiO_2 of the slag.

Fig. 11. The influence of the deviation of the Fe % of the sinter.

siderable variation in the Fe content of the sinter during rather short period. Two kinds of predicted hot metal temperatures are shown in Fig. 11; one is simulated under the condition that the Fe content of the sinter is regarded as a constant, the other is simulated by the use of the measured and tracked Fe content data of the sinter. It is clear that the latter prediction agrees better with actual hot metal temperature. Consequently, it was confirmed that the prediction accuracy of the hot metal temperature is improved by the use of the measured and tracked data of the sinter. The control of each component of the sinter at a desired value has promoted at the sinter plant, because the influence of the fluctuation of the Fe content of the sinter on the hot metal temperatures is very large and cannot be compensated completely.

2. Check of the Accuracy of Blast Flow Rate

The accurate measurement of blast flow rate is necessary for the estimation of the iron-production rate in the blast furnace. The blast flow rate is measured by an orifice system at the inlet of the hot stove. The total accuracy of the measuring system had not been known, although the signal processing units have been well maintained with the accuracy of $\pm 0.5\%$ F.S. In order to investigate the accuracy of an orifice system, the velocity distribution was measured by a pitot-tube at the upstream of the orifice and was compared to the orifice measurement. The results are

Fig. 12. Calibration of blast flow rate by pitot-tube.

Fig. 13. Comparison of two measurements (at the taphole and at the skimmer).

shown in Fig. 12. The figure shows more than 3 % deviation between two measurements. This deviation is significant because the pitot-tube was calibrated within $\pm 1\%$ accuracy in the laboratory. It may be caused by the velocity distribution of an incomplete turbulence shown in Fig. 12. The deviation between the actual iron production rate and the calculated one could be decreased by the correction of the error of the orifice measurement.

3. Improvement of Measurement of Hot Metal Temperature

(1) Improvement of Measurement Timing of Hot Metal Temperature

It is desirable to measure the hot metal temperature continuously just after the hot metal is tapped from a blast furnace. But it is difficult. So the hot metal temperature had been usually measured at the skimmer in the conduit at the middle of the tapping time for each torpedo car. In order to compare these two measurements, namely, at the taphole and at the skimmer, these values were measured simultaneously by an immersion type thermo-couples. The results are shown in Fig. 13. The figure shows that the temperature measured at the skimmer was rather lower than that measured at the taphole at the beginning of a tapping, because the hot metal had been cooled by the refractory of conduit at that period. So the hot metal temperature must be measured at the time

when hot metal have been tapped in certain amount sufficient to warm up the refractory of conduit. Then it was decided that the measurement must be carried out at 40 min after the start of tapping. By the use of these measurement value, the hit percentage of the temperature estimations has improved over 5 %.

(2) Averaging the Hot Metal Temperature of Each Taphole

The hot metal temperature of each taphole has some deviations among each other. Figure 14 shows that the hot metal temperature of No. 1 taphole was always higher than that of No. 3 taphole. It seemed to be caused by the unbalance in the distribution of charged material in the blast furnace. The three tap averaged temperature is adopted as the indication of hot metal temperature in the blast furnace, because the present model controls the heat level which is averaged over the cross section area of the blast furnace. Figure 14 also shows that the TS_5 calculated from the model agrees well with the three tap averaged hot metal temperature.

IV. Application of Control System

1. Improvement of Control Model (Adaptive Control)

In order to coincide the model calculation with the actual blast furnace condition, the output data of the blast furnace, such as the top gas analyses and the hot metal temperature are used for the adjustment of the parameters in the model. Figure 15 shows an example of the usage of the adaptive feedback of the top gas analyses. By the use of the top gas analyses, the

T_{pig} : Hot metal temperature of each tap
 $T_{pig(3)}$: 3 tap averaged hot metal temperature
 $\hat{T}_{pig(3)}$: Estimated hot metal temperature
1, 2, 3: Taphole number

Fig. 14. Deviation of the temperature of hot metals tapped from 3 tapholes.

Fig. 16. A schematic diagram of the computer control system.

calculations of the solution loss reaction rate (R_4) and hot metal temperature (TS_5) are modified. Owing to these adaptive feedback with highly accurate gas-chromatography, the estimation accuracy of the model is improved.

2. Practical Application

1. Computer Control System

Figure 16 shows a schematic diagram of the computer control system of the hot metal temperature. The hot metal temperature is predicted every 10 min by the use of the mathematical simulation model. The indications of the change in operation variable is computed for the compensation of the difference between the predicted hot metal temperature and the target value. Besides the automatic control of the hot metal temperature, the system monitors the abnormality to the furnace condition. When the sudden abnormal change in operation data is detected, such as the change in top gas analyses and the change in the burden descending velocity, the control system is stopped automatically and the suitable alarms are immediately given to the operator for the recognition of the abnormalities of the furnace conditions.

Fig. 15. An example of the simulation by the model with/without the adaptation to top gas compositions.

Fig. 17. Comparison between manual and automatic control periods.

2. Application Results

The computer control system was introduced to Kokura No. 2 BF and since 1977 the oil injection rate has been automatically controlled by this system. As Fig. 17 shows, it was confirmed that variation in the hot metal temperatures was decreased by the adoption of the automatic control. The operation with 10 to 15 °C lower hot metal temperature than in former time has been carried out and fuel ratio has been decreased. The automatic computer control was applied for 2.5 years until the blow out of the furnace and had contributed to the stable and low cost blast furnace operation.

V. Conclusions

The measurement accuracies, which were required for the control of the hot metal temperature within 5 °C of target, were investigated by the use of the mathematical simulation model of blast furnace process. It was found that the measurement accuracies of the N₂ content and the CO₂ content of the top gas, the Fe content of burden and the blast flow rate were not enough. The following improvements were carried out in order to improve the accuracies of the calculations of the material and heat balances and the accuracies of the prediction of hot metal temperature.

- 1) Development of the highly accurate gas-chromatography
- 2) Development of the sinter property tracking sys-

tem

- 3) Check of the measurement accuracy of the blast flow rate
- 4) Improvement of the measurement timing of the hot metal temperature

Owing to these improvements, the automatic computer control system of the hot metal temperature could be applied to Kokura No. 2 BF for 2.5 years until the blow out of the furnace, and this system had contributed to the stable and low cost operations.

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REFERENCES

- 1) M. Hatano, Y. Misaka, Y. Matoba and K. Otsuka: *Trans. ISIJ*, **22** (1982), 524.
- 2) M. Hatano, Y. Matoba, K. Otsuka, M. Yoshiki and T. Miyagi: *Trans. ISIJ*, **22** (1982), 534.
- 3) Y. Sakamoto, N. Fujino, S. Inenaga, T. Yamamoto and K. Yoshino: *Tetsu-to-Hagané*, **65** (1979), S596.