Development of Monitoring System for Lumpy and Cohesive Zones in the Blast Furnace*

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Synopsis

At No. 2 blast furnace of Sakai Works, effort is being made to develop and practically apply new types of sensors (magnetometer, and gas flow meter) and probes (shaft diameter probe, shaft wall probe, etc.) for accurate measurement of gas flow distribution and burden behavior in the lumpy zone. Mathematical models for estimation of the state of lumpy zone and the outer profile of cohesive zone in the furnace have been developed. The cohesive zone model is composed of simultaneous ordinary differential equations including heat transfer equations and material balance equations, and the Runge-Kutta-Gill method is employed to obtain numerical solution for this model. By using the information from these new probes and models several new findings have been obtained.

I. Introduction

As it has been made clear that the distribution profiles of the lumpy and cohesive zones in the blast furnace have a great effect on the flow of gas within the furnace and the efficiency of reactions between the burden materials and the gas, studies^{1,2)} on the measurement and control of gas flow and burden distribution profiles are underway. At Sakai No. 2 BF, efforts are being made to develop and practically apply new types of probes for accurate measurement of gas flow distribution and burden behavior in the lumpy

zone and mathematical models for estimation of the state of lumpy zone and the profile of cohesive zone. A monitoring system for lumpy and cohesive zones in the blast furnace has been developed to help to clarify the phenomena occurring in the furnace and improve blast furnace operation on the basis of the information obtained from the above-mentioned probes and models.

II. System Configuration

This system consists of hardware, such as throat diameter probe (hereinafter referred to as "TDP") for measurement of gas flow distribution and burden profile in a diametral direction at the burden top and shaft diameter probe (hereinafter referred to as "SDP") for measurement of gas flow distribution and burden behavior in a diametral direction at the shaft and shaft wall probe (hereinafter referred to as "SWP") for measurement of burden behavior in the circumferential direction, and soft-ware, such as a mathematical model for estimation of the state of lumpy zone and the outside profile of the cohesive zone.

The mathematical model for estimation of the out-

Fig. 1. Configuration of monitoring system for lumpy and cohesive zones in the blast furnace.

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side profile of the cohesive zone is composed of simultaneous ordinary differential equations concerning heat transfer and chemical reactions. In calculation, gas temperature and chemical composition and the state of lumpy zone and total mass balance and heat balance data at the indirect reduction zone are needed. The state of the lumpy zone, such as layer thickness of ore and coke, ratio of thickness (L_o/L_c) and descending speed of burden is measured by magnetometer installed on "SDP" and "SWP".

The system configuration is outlined in Fig. 1.

III. Development of Probes and Sensors

1. Technique for Sensing Burden Behavior by Magnetometer³⁻⁵⁾

For measurement of the condition of ore and coke layers and the ore-to-coke ratio in the blast furnace, a method has been developed in which the boundary between the ore and the coke layer is detected from the difference in magnetic permeability between the ore and the coke layer by the use of a multiple type magnetometer (hereinafter referred to as "MM").

As the temperature of the ores is below Curie's temperature 780 °C, the ores keep their ferromagnetic

property. Therefore the difference of magnetic permeability between the ore and the coke is significant in the upper shaft. As the ore and coke continuously descend in a layered state, the magnetometer output signal (E_o), which is shown as the relationship between the magnetic field and the distance from the magnetometer to the ore layer, is converted to the time variant waveform function shown in Fig. 2.

The time period from a minimum A to the following maximum C of the output waveform of the magnetometer and the time period from the maximum C to the following minimum A mean the time period required for ore layer, to pass through the magnetometer and the coke layer to pass through it, respectively.

Positions A and C indicate the boundary between the ore and the coke layer.

Figure 3 is a schematic drawing of "SWPs" with magnetometer installed in a blast furnace. A pair of upper and lower "SWPs" of water-cooled double tube construction are installed in such a manner that they protrude into the furnace by about 600 mm and are 400 mm away from each other. The difference in phase between output waveforms from the upper and lower probes represents the time required for burden descent.

Accordingly, the information on burden, such as descending speed, layer thickness ratio and mass descending velocity in the vicinity of the probes can be estimated by processing the waveform signals.

An irregular pattern of waveform shows the existence of a mixed layer.

"SWPs" should be installed at the area below Curie's temperature.

At Sakai No. 2 BF, they are installed in the upper part of the shaft 3 to 4.5 m below the stock line.

For the installation of "MM" in the blast furnace, the "MM" and the magnetic field generator should be small in size and simple in structure to make them completely air-tight and facilitate their cooling. Accordingly, the core, the permanent magnet and the oscillation circuit are built linearly in a single unit.

The water-cooled protective tube is made of non-magnetic stainless steel which does not have a magnetic shielding effect.

2. Shaft Diameter Probe "SDP"

The "SDP" is essential equipment for the detection of gas flow distribution and burden behavior distribution in the diametral direction of the furnace.

Fig. 2. Principle of measurement by magnetometer.

Fig. 3. Schematic drawing of shaft wall probe.

Its cross-sectional view is shown in Fig. 4. The above-mentioned “MM” to be used for measurement of burden behavior in a diametral direction must be kept installed in the furnace for a long time. Accordingly, the “SDP” has been developed as a multi-purpose probe which can be kept installed in the furnace for a long time and is capable of measuring not only burden behavior but also temperature and gas composition. The first trial “SDP” was installed in the furnace in 1975. Since then, the “SDP” has undergone various improvements in shape and function.

The results of use and features of the 5th “SDP” are given in Table 1.

Figure 4 shows a cross section of shaft diameter probe “SDP” and layout of detectors for temperature measurement and gas sampling. Eleven thermocouples are located in a diametral direction, and equipped with the following functions.

- 1) Automatic temperature measuring system by sequencer (N_2 purge at all times, Temperature measurement with N_2 off)
- 2) Frequency of temperature measurement: every 30 min (30 min purge and 30 min scanning of temperature.)
- 3) Thermocouple can be exchanged during furnace scheduled delay.

Results of replacement of thermocouple 196 days are shown below.

Thermocouples near the center gradually lose their function because of high temperature and Zn deposition on the surface.

Five gas sampling tubes are located in a diametral direction, and equipped with the following functions.

- 1) Automatic gas analysis system by sequencer (N_2 purge at all times, gas sampling with N_2 off, steam purge, 10~20 min per day for pipe cleaning)
 - 2) Frequency of gas analysis: every 4 hr
- The gas sampling tube G_6 at the center clogged

after 125 days of use.
The gas sampling tube ($G_1 \sim G_4$) in the intermediate and peripheral parts remained unclogged for 196 days.

Seven pairs of magnetometers are located in a diametral direction. “SDP” is composed of large and small water-cooled stainless pipes, on which a pair of upper and lower magnetometers are equipped.

Output waveforms from magnetometer are inclined to present slight distortion because ore and coke passing near the probe are influenced by SDP wall effect. So several improvements were tried during the 1st to the 5th SDP trials, and rectifying box and cocks comb plate were installed, as is shown in Fig. 4.

In the 5th SDP trial, good waveforms from the upper “MM” were obtained, but waveforms from the lower “MM” were still distorted slightly.

3. Gas Velocity Measurement by Pitot Tube and Hot-wire Sensor

For measurement of comparatively low flow velocity of gas which contains large quantities of dust and whose pressure and temperature fluctuate, a new type of gas velocity meter has been developed by combining a Pitot tube and a hot-wire velocity meter.⁶⁾

A schematic drawing of this velocity meter is shown in Fig. 5.

When measurement is not conducted, the Pitot tube and communication pipe are purged with N_2 gas with the valves V_1 and V_4 opened and valves V_2 and V_3 closed. When measurement is started, the valves V_1 and V_4 are closed to stop the flow of

Table 1. Result of use of 5 th “SDP”

Period of use	From May 8, 1978 to November 30, 1978 196 days in total (removed for inspection)
Total tonnage of materials charged	1 434 943 t
Total number of charges	14 918 charges
Performance condition	Slip : 385 times, Hanging : 1 time in total
Examination of probe appearance after use	Body cracks : None Max. deflection of the body : 115 mm Max. wear Large tube : 1.20 mm Small tube : 1.25 mm

Fig. 4.
Cross section of shaft diameter probe “SDP” and layout of detectors.

purge gas. When the valves V_2 and V_3 are opened under the above-mentioned condition, a small flow of purge gas occurs in the measuring conduit by the differential pressure produced in the Pitot tube. This purge gas comes into contact with the hot-wire sensor of the hot-wire velocity meter. If the measuring time is limited to the time required for the gas entering from the Pitot tube into the conduit to reach the valve V_2 , clean purge gas flows to the hot-wire sensor to eliminate the contamination or damage of the hot-wire sensor by dust. The measuring conduit and sensor are placed in a thermostatic box to keep the gas flowing to the sensor at a constant temperature.

These meters are installed on the throat diameter probe "TDP" as shown in Fig. 6. The gas velocity distribution at the furnace top is measured by the "TDP", which has a shape similar to the angle of inclination of the burden and a hinge at its center. Trend example of gas velocity and gas temperature in the central and peripheral zones is shown in Fig. 6.

IV. Development of Mathematical Model for Estimation of the State of Lumpy Zone and Cohesive Zone in the Furnace

A mathematic model for estimating the state of the lumpy zone and the outer profile of the cohesive zone in the furnace by receiving the information from the new probes described above has been developed.

Fig. 5. Schematic drawing of gas velocity meter by Pitot tube and hot-wire sensor.

Fig. 6. Pitot tube and hot-wire sensor in blast furnace applications and example of measured value.

The basic ideas of the model are outlined below:

(1) This model has a function to estimate the outer profile of the cohesive zone, and the distributions of gas and solid, such as temperature, gas composition and reducibility in the various states of the lumpy zone.

(2) The main information to be received from the probes into the model are the temperature distribution measured by the "TDP", the temperature and gas composition distributions measured by the "SDP", and the layer thickness and descending speed distribution of ore and coke measured by the magnetometer installed on the "SDP".

(3) The distributions of gas velocity and burden descending speed are estimated by solving the heat transfer equations for gas and solid, using the temperature distributions measured by the "TDP" and "SDP".

(4) Calculated gas velocity distribution and the burden descending speed distribution are corrected so as to conform to the total material balance in the blast furnace.

(5) The kinetics of indirect reduction of ore by CO and H_2 are calculated on the basis of a single inter-surface reaction model developed in consideration of intergranular diffusion resistance and chemical reaction resistance.

(6) The simultaneous ordinary differential equation consisting of the heat transfer equations for gas and solid and the material balance equations for CO, CO_2 , H_2 and O_2 are calculated by Runge-Kutta-Gill method in order to estimate the outside profile of cohesive zone and the state of lumpy zone.

(7) The outside profile of cohesive zone is estimated, regarding the positions, where CO_2 is 0 %, as the outside surface of the cohesive zone.

It is well-known that softening of reduced ores in the furnace starts in the temperature range of $950 \sim 1100^\circ C$, and that so-called "thermal reserve zone" exists near the same temperature range. So it is fairly difficult to clarify definitely the positions of the outside surface of cohesive zone on the basis of tempera-

ture only.

Solution loss reaction will dominate the furnace area of $\text{CO}_2=0$, where a lot of endothermic heat should be compensated for by thermal exchange between gas and solid. For this reason, both temperature must increase rapidly up to softening and melting temperature of burden. These are the reasons why the positions, $\text{CO}_2=0$ are regarded as the outside surface of cohesive zone.

V. Examples of Analysis and Application of the Developed Monitoring System in Sakai No. 2 BF

1. Examples of Application of the Data Provided by "SWP"

"SWPs" present burden behavior information in the circumferential direction of the furnace, such as speed of descent, ratio of thickness of ore and coke layers (L_o/L_c) and mass velocity. As shown in Figs. 7 and 8, correlations were observed between variations in ore mass velocity in the circumferential direction and the frequency of slip occurrence and between variations in L_o/L_c and variations in Si content. It has been confirmed that minimization of burden deviations in the circumferential direction is effective for good operation.

Figure 9 shows waveform examples of "SWP" magnetometer when changing the protrusion length from the wall for the purpose of measuring the existence of a mixed layer near the wall. In the case of 590 mm protrusion, waveforms are sensitive enough to detect the boundary between the ore and the coke layer. But in the case of 340 mm and 440 mm, waveforms become irregular, which indicates the existence of a mixed layer as shown in the schematic drawing of Fig. 10.

As the burden behavior such as thickness of coke and ore layers and descending speed cannot be detected in mixed layer, at Sakai No. 2 BF, protrusion length of "SWP" is set at about 600 mm from the furnace wall. SWP's give information concerning the existence and range of a mixed layer near the wall.

2. Examples of Application of the Data Provided by "SDP"

Figure 11 shows changes in L_o/L_c in the diametral direction with changes in the notch of the movable armor. When the coke notch is increased and much

coke is objected to charge toward the center, L_o/L_c in the range from the furnace wall to 1 800 mm (M_1 to M_3) increases gradually but tends to decrease at M_4 . Little influence of coke notch is observed at M_5 and M_6 .

Fig. 7. Relation between variations in ore mass velocity in circumferential direction and frequency of slip occurrence.

Fig. 8. Relation between variations in L_o/L_c in circumferential direction and variations in Si content within a day.

Fig. 9. Waveform examples of "SWP" magnetometer including a test of changing positions.

Fig. 10. Schematic drawing of mixed layer in the vicinity of the furnace wall.

Fig. 11. Relation between movable armor notch and L_o/L_c distribution in the diametral direction.

It is confirmed that movable armor is more effective for the adjustment of the peripheral L_o/L_c .

As above-mentioned, the new probes give outstanding information on the burden behavior which hitherto could not be obtained.

3. Examples of Application of the Mathematical Model for Estimation of Outside Profile of Cohesive Zone

Sakai No. 2 BF has been obliged to continue curtailed operation under recent economic circum-

Table 2. Typical operating indices of Sakai No. 2 BF in three periods corresponding to Fig. 12.

	Period A	Period B	Period C
	April, 1979	August, 1979	March, 1980
Features	Oil injection Fuel rate: 443 kg/MT Pellet Ratio: 18.6 %	Oil injection Fuel rate: 443 kg/MT Pellet Ratio: 21.0 %	All coke Fuel rate: 477 kg/MT Pellet Ratio: 34.6 %
Productivity (MT/day/m ³)	1.27	1.22	1.36
Fuel rate (kg/MT) (Coke+Oil)	443 (415+28)	473 (444+29)	477 (477+0)
CO utilization ratio (%)	53.5	49.5	51.7
[Si] in pig iron (%)	0.68	0.78	0.63
Frequency of slip (times/day)	3.3	9.6	12.4
Heat flow ratio of solid and gas	0.782	0.824	0.842

stances.

The mathematical model for estimation of lumpy and cohesive zone was applied to Sakai No. 2 BF in the period from March, 1979 to April, 1980.

Relations between operational results and model estimation were investigated in the following typical periods of operation.

Figure 12 shows the results of analysis by the mathematical model for estimation of the lumpy zone and the outside profile of the cohesive zone in the periods, (A), (B), (C), shown in Table 2.

Figure 12(A) shows examples of operation at low fuel rate with smooth descending of burden and good permeability under oil injection.

Furnace gas flow through the central area develops satisfactorily and descending speed of burden is uniform in the diametral direction. The outside profile of the cohesive zone near the furnace wall exists in the lower region of the stack, which agrees with the stove temperature distribution obtained from the middle region of the stack cooling staves.

Figure 12(B) shows one example of period B in which performance conditions (permeability and descending of burden) became unstable and fuel rate increased by 30 kg/MT compared with period A. The descending speed of the burden near the furnace wall becomes fairly rapid and gas flow velocity in the center is limited, which means intensive central gas flow is not obtained.

The outside profile of the cohesive zone is shifted to the upper zone near the furnace wall. According to the change of cohesive zone profile, stove temperature decreases in the lower region of the stack and increases in the middle of the stack.

Fig. 12. Examples of relation between the outside profile of cohesive zones ($\text{CO}_2=0\%$) and temperature distribution in a blast furnace.

Figure 12(C) is an example of Period C in which fuel rate is nearly the same as in Period B, but coke rate increases by 33 kg/MT accompanied by the all coke performance.

Increase of heat flow ratio between gas and solid especially in the peripheral region of the furnace is observed, which is caused by all coke operation and rapid descent of the burden near the wall.

The estimated outside profile of the cohesive zone is rather different from the above mentioned periods A and B. Namely the softening zone near the wall lowers up to the bosh, which is understood by the actual stave temperature profile. Changes in the outside profile in the center of the furnace are caused mainly by the influence of high pellet ratio operation.

Typical examples are reviewed through the mathe-

Fig. 13. Relation between upper end position of root, [Si] and slip.

Fig. 14. Correlation between descending speed of materials and distance from a stock line to the outside surfaces of cohesive zone root.

mathematical model analysis mentioned above.

In Sakai No. 2 BF, slips tend to increase with the recent production cutback. Figure 13 shows the relation among the "upper end position of the cohesive zone root" (the position where the ore begins to soften near the furnace wall estimated by the mathematical model), the frequency of slip occurrence and Si content in hot metal.

The relation between the descending speed of burden in the vicinity of the furnace wall and the distance from the stock line to the upper end position of cohesive zone root is shown in Fig. 14. A close correlation is observed between them. Namely, it is considered that the cohesive zone moves downward as the descending speed increases.

The optimum cohesive zone profile seems to vary with production rate and other performance conditions. In curtailed operation, consideration should be given to developing central gas flow, and improving the heat capacity of the dead man zone where the ore is melt down.

For Sakai No. 2 BF, the optimum cohesive zone profile is given as follows from operational analysis. The upper end of the root is in the lower part of the shaft in the range 16 to 19 m below the stock line, its apex is at a position of 5 to 8 m below the stock line, and the outside profile of the cohesive zone bulges toward the furnace center.

To satisfy these conditions, the temperature in the

central region of "SDP" should be higher than 600 °C, η_{CO} in the central region about 30 %, and the temperature in the central region of "TDP" higher than 400 °C.

VI. Conclusion

It was confirmed that the monitoring system for lumpy and cohesive zones in the blast furnace helps to investigate the phenomena occurring in the blast furnace and improve blast furnace operation techniques by providing useful information as described above.

We will make greater efforts for further improvement of the reliability of the system and the controllability of the blast furnace.

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