Development of a Visual Information Technique of Nonstationary Fluctuations in a Blast Furnace Process

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By turning stave temperature and shaft pressure data, collected by a number of sensors spatially located circumferentially and vertically in the blast furnace, into images distributed in two dimensions, we have succeeded in quantitatively and objectively visualizing shaft pressure variations and spatial changes caused by slipping in the blast furnace. In addition, combining the two-dimensional distribution of secondarily processed data of changes in space and time with the progress of operation data enables early detection of shaft pressure fluctuations. The conjecture that the uneven distribution of voids in the blast furnace may be the cause of shaft pressure fluctuations has been confirmed by our model experiments. It has been also found that there exists a relationship between the cohesive zone root position, assumed by the visualized two-dimensional image of the stave temperature change over time, and the origins of shaft pressure fluctuations. KEY WORDS: blast furnace; pressure distribution; stave temperature; unstable operation; cohesive zone.

1. Introduction

The reduction in the amount of reducing agents used in blast furnaces is an important task for improving global environment protection and solving energy saving problems. The main areas to be rectified include global warming by CO₂ and the exhaustion of fossil fuels. The same is also important in the iron-making processes from the viewpoints of extending coke oven life and improving production capacity. From the viewpoint of using a lesser amount of reducing agents, techniques have been developed including those for improving the rate of reducing gas utilization by enhancing ore reduction and coke reaction, and for decreasing the need for calorific power by minimizing Si in pig iron. In order to actually decrease the input rate of the reducing agents however, it is essential to continually operate under stable conditions that are near the critical thermal condition. Nevertheless, to ensure stable operation, phenomena occurring during nonstationary operation must be elucidated first. Various nonstationary phenomena occur during blast-furnace operations, including routine fluctuations due to raw material component variations, daily thermal fluctuations, and burden descending fluctuations, with large-scale fluctuations resulting in operational disorder. These phenomena usually last for several minutes to several hours, varying from case to case, and can be caused by abnormal heat transfer, reaction, gas flow, or solid flow. Specifically, actual abnormal phenomena can be in the form of a sharp drop in hot metal temperature, fluctuations in furnace top gas component composition, a slip or drop or hanging of burden, shaft pressure fluctuations, or abnormal gas flow such as fluidization, or channeling (see Fig. 1). These phenomena are often interrelated, and many analyses have been performed in the past.1–6)

Various physical models have been developed for the elucidation and control of these nonstationary phenomena,7–10)
and three-dimensional nonstationary physical models in particular, have been being developed in recent years in an attempt to quantitatively evaluate and analyze nonstationary phenomena (dynamic behaviors and characteristics).

Quantitative analysis and control techniques were also developed by applying AI.12–17) Despite the progress of such physical models and AI, and the development in the varieties of sensors and probes, however, the grasp and prediction of nonstationary phenomena in the actual blast furnaces are largely due to the experience and skills of on-site operators.

One of the reasons why the identification and prediction control of nonstationary phenomena have not necessarily been automated is because the hardware was not sufficiently advanced. Since the nonstationary phenomena take place in certain radial, vertical, and peripheral zones within blast furnaces, the sampling and analysis of two- or three-dimensional data are required. In addition, in terms of time, phenomena that last for several minutes or several hours must be continuously traced. However, blast furnaces in the past were not all equipped with hardware and a database capable of storing a vast volume of data for a long period was measured by sensors and sampled in a short time. Available techniques were also not sufficient to perform three-dimensionally, spatially, efficiently, and quantitatively analyses. In addition, the hardware was unable to evaluate the large volume of stored data. For these reasons, the treatment and quantitative analysis of blast furnace operation data were not sufficient.

Recently, however, a great deal of improvement in computing capacity has been combined with the spread of low-cost hardware and database systems capable of storing a large volume of digital data. This has allowed the enhancement and prevalence of digital image processing technologies, and has enabled sampling to be performed in a very short time. It has also enabled mass-store blast furnace operation data for a long period to be achieved, and allowed the reduction of the blast furnace operation data to be processed into image information.

This paper reports the results of analysis of nonstationary phenomena in blast furnaces, obtained by two-dimensionally visualizing stave temperature and shaft pressure data, using the above-mentioned technologies.

At operation sites, this visualized image system is updated in minutes or few seconds and is used for operation monitoring.

2. Examples of Shaft Pressure and Burden Descent Variations

First, we analyzed nonstationary fluctuations, i.e., shaft pressure variation and slipping, using the transition-with-time charts of sounding and furnace top gas component composition that used to be monitored in practice, with particular attention paid to the stock condition and reduction in the furnace.

Figure 2 shows examples of the variations over time. At about 6 o’clock, the shaft pressure in the zone from the bosh to the belly sharply rose, and a large slip occurred at about 7:20 where the pressure fell to its original level. A
CO increase and CO\textsubscript{2} decrease started approx. two hours before the slipping, and a subsequent CO+CO\textsubscript{2} rise, and concurrent furnace top temperature rise are seen from the results of the furnace top gas analysis. This appears to suggest that a bubbling zone was produced in a certain region in the furnace, resulting in a lower stock charge in the furnace and the discharge of unabated high-temperature gas from the furnace top. It is also conceivable that a high-temperature gas with a high CO content ascended in the furnace to expand the solution loss area, resulting in a CO+CO\textsubscript{2} increase. The slip entailed an abrupt descent of the burden, resulting in the restriction of reduction and solution loss reactions, CO and CO\textsubscript{2} decreases, and an eventual CO+CO\textsubscript{2} increase.

However, the information thus obtained alone is not sufficient to be able to estimate the behaviors that vary over time and in space vertically and circumferentially within the furnace. To compensate for the insufficiency, we visualized and indexed two-dimensional behaviors with respect to stave temperature and shaft pressure, whose two-dimensional information is spatially obtainable although the information is limited to furnace surface information.

3. Two-dimensional Visualization of Stave Temperature and Shaft Pressure Data

3.1. Data Visualization\textsuperscript{18–21}

By projecting the positions of the stave thermometer and shaft pressure gauge sensors installed in a blast furnace upon a two-dimensional plane extending in the height and circumferential directions of the furnace, followed by arithmetic calculation, we plotted the obtained sensor data into contour charts, and vector diagrams. For regions not covered by the sensors, we obtained values by spatially interpolating the values of the sensors. Specifically, images are processed by the following procedure. (1) A profile of the bottle-shaped blast furnace is projected on a two-dimensional plane in the furnace height and circumferential directions. (2) Values of measurements by the sensors are placed in the corresponding locations in the two-dimensional plane, by accurately relating them to the corresponding particulars of the three-dimensional location information of the sensors. (3) Measured data are plotted to draw out an equivalent diagram, a contour diagram, and a vector diagram. (4) For each area in the projected two-dimensional plane where no sensor is located, a virtual grid is set in, and values on the grid are calculated using actual measurements in its vicinities, followed by spatial interpolation with Euclidean distances. (5) As the sensors are not necessarily located at equal intervals in the two-dimensional plane, we develop a high-speed interpolation and iso-line searching algorithm by which we can perform on-line analysis for sensors in any location.

Figure 3 shows an example of the two-dimensional visualization of the shaft pressure variation, in which the axis of the abscissas represents circumferential angles of the furnace, the axis of the ordinates represents the height positions, the asterisk (*) represents the sensor position, and the arrow represents the spatial rate of change, \textit{i.e.}, shaft pressure drop.

Compared with the transition charts shown in Fig. 2, the positions where pressure variations occurred and the pressure rise transition in the space, are seen more easily in Fig. 3. For stave temperature variations, too, we similarly visualized them two-dimensionally. Seeing that various behaviors in the furnace are considered to be taking place with lags in time and space, we calculated and two-dimensionally visualized, as discussed in the following section, not only the ongoing data and the rates of changes over time but also the rates of changes with past records taken into account.

Figure 4 shows the transition of the distributions of the spatial differential rates of shaft pressure and the stave temperature in the vertical and the circumferential (from top figure to bottom figure: 0-, 90-, 180- and 270-deg.) directions. The axis of abscissas represents time as seen in Fig. 2. It is easily visually understandable that at about 6 o’clock, spatial differential rates of shaft pressure arose chiefly in the direction of 0 deg., accompanied by a stave temperature rise.

3.2. Analysis of Shaft Pressure Variation Based on Two-dimensionally Visualized Images

Figures 5(a) to 5(e) show the shaft pressure distributions, spatial differential rates of shaft pressure distributions, and the time differential rates of the shaft pressure, as well as the stave temperature distributions and the time differential rates of the stave temperature, at 90 min intervals at times corresponding to those shown in Fig. 2, all being represented in the form of two-dimensionally visualized images.
Figure 2 highlights that the shaft pressure sharply rose at about 6 o'clock and the slip occurred at about 7 o'clock, and it is further indicated from the shaft pressure distribution (in Fig. 5(a)) that the furnace bottom pressure sharply rose between five thirty and seven in the 0-deg. direction. The figure also appears to indicate that although the furnace bottom pressure rise subsided at 8 o'clock after the slip, the circumferential pressure distribution imbalance remains, with the cause of the pressure variation not completely removed.

The stave temperature rose in the 0-deg. direction at 7 o'clock (Fig. 5(d)), denoting a relationship with the shaft pressure rise. As for the time differential rates of the stave temperature distribution (in Fig. 5(e)), temperature rise variations are already seen at about five thirty at the bosh and the bottom levels in the 360-deg. direction, denoting a sign of shaft pressure variation. Figure 5(c) shows the time differential rates of shaft pressure. If no variation occurred, its image assumes an overall light gray. It is seen from Figure 5(c) that the shaft pressure distribution significantly varied around five thirty. It can therefore be stated that a bubbling zone occurred in a certain region within the furnace at about five thirty, and it materially affected the stock condition. When we observe the gas component data variations from such a point of view, we see a CO increase after 5 o'clock, which is a sign of bubbling.

Close examination of Fig. 5(b) reveals two points. Firstly, a zone where the spatial differential rates of shaft pressure is abnormally high (the pressure gradient is larger than in the neighboring area), and secondly, a zone where the spatial differential rates of shaft pressure is abnormally low (the pressure gradient is smaller than in the neighboring area). These irregularities are noticed as a pair mainly in the height direction, and the shaft pressure fluctuations occur where the pressure gradient anomaly of the pair disappears. At the same time, the burden descent stagnates. The indications may be that the cancellation of the burden descent stagnation, that is, the occurrence of the slip or drop, causes shaft fluctuations to cancel the pressure gradient anomaly.

Thus, we can easily see fluctuations in space in a furnace in its height and circumferential directions in the course of time by two-dimensionally visualizing stave temperatures, pressure distribution, and their analyzed values. Furthermore, for shaft pressure variations, the visualization permits faster and surer detection of them than using furnace top sensors only.

4. Verification of Visualized Shaft Pressure Image by Model Experiment

The gas flow and solid flow condition in a blast furnace is maintained from the change of two-dimensionally visualized images of shaft pressure and stave temperature, as discussed in the foregoing section. However, since the two-dimensionally visualized images cannot provide information related to the depth, i.e., the radial direction, we cannot identify the cause of the change of the two-dimensionally visualized images. To see the in-furnace condition three-dimensionally, an indirect estimation by model experiments or three-dimensional nonstationary model calculations are necessary.

Here, in the following subsections, we report the results of the measurement and analysis of the furnace wall pressure distribution obtained by a model experiment that we performed on the assumption that the variation in the shaft pressure distribution is caused by the accumulation of dust or other deposits on the blast furnace wall.

4.1. Experimental Apparatus and Method

The experimental apparatus is a hopper approximately one-tenth in size of an actual blast furnace, and its main body is a rectangular parallel-pipe (500 mm wide, 2000 mm high, and 100 mm deep) made of acrylic resin. Gas can blow into either side of the hopper wall at its bottom, and the back of the hopper has holes for pressure measurements (see Fig. 1).

A wooden block imitates the deposits and is installed in the middle of the acrylic hopper, with a cube of steel wire mesh imitating a hollow and containing 3-mm alumina balls (at a bulk density of approx. 2190 kg/m3 and a void rate of 0.392). One side of the wooden block and the wire-mesh cube is closely fixed to the back of the hopper wall at its bottom, and the back of the hopper has holes for pressure measurements (see Fig. 1).

Alumina balls are discharged from the hopper bottom, while being charged into from the hopper top, forming a descending of burden. Concurrently, air is supplied from a
When the alumina particles are moving towards the hopper bottom, the pressure sensors at the holes in the back of the hopper measure the pressure distribution. The pressure sensors are located at 8 points vertically at intervals of 100 mm, and at 2 points radially at intervals of 200 mm, at 16 points altogether. The air flow rate is 1000 L/min, which comes to an air flow speed of 0.333 m/s with an average pressure loss of 1.65 kPa/m.

### 4.2. Experimental Results

The experiment was performed in the following three cases: 1) a hollow is formed with a wire mesh in the center, 2) a wooden block is located in the center, and 3) a wooden block is located above the center and a hollow is formed by a wire mesh below the center.

Figure 7 shows the experiment results. The upper section of the figure shows the shaft pressure distributions, and the lower section shows the spatial differential rates of shaft pressure calculated by the shaft pressure distributions. The lateral points of the shaft pressure measurement were the hopper center and the one on the left side of the hopper.
only (see Fig. 6), but we also calculated the shaft pressure distribution and the spatial differential rates of shaft pressure on the right-hand side assuming that they are symmetrical. In Fig. 7, the areas occupied by the wire mesh and wooden block are shown as blank and gray rectangles respectively. We can see from this figure that the spatial differential rates of shaft pressure is small in the hollow, and that the pressure gradient is high in the area occupied by the wooden block, which represents deposits. In addition, when both a wooden block and a hollow coexist above one another, we can see a zone with a high spatial differential rates of shaft pressure appearing near the wooden block and a zone with a low spatial differential rates of shaft pressure near the hollow.

| 1) A hollow formed in the central region | 2) A wooden block installed in the middle position | 3) A wooden block plus a wire mesh installed in the middle positions |

Our discussions are focused on the cohesive zone root as the cause. In other words, we are examining the relationship between the root position of the cohesive zone estimated by using two-dimensionally visualized images of the stave temperature, and the position where the shaft pressure fluctuation occurred.

4.3. Discussion

The experimental results indicate that a zone with a high spatial differential rates of shaft pressure and a zone with a low spatial differential rates of shaft pressure, as observed in actual blast furnaces, may appear as a pair. This may occur when a region with a low void fraction rate exists, compared to the void fraction rate of the region under it, which is relatively higher as seen in b), or when a region with a low void fraction rate and a region with a high void fraction rate appear in a pair as seen in c).

In actual blast furnaces, a typical cause that produces a hollow as seen in b), may be that the burden descent becomes stagnant for some reason (to a state of “hanging”), whereby dust or debris sticks to the stagnant portion. At the bottom, the stock keeps falling, leaving a hollow. A typical result as seen in c), which implies that a low void fraction rate region is formed by the sticking or accumulation of dust, and a high void fraction rate subsequently occurs as a result of the burden descent stagnation or disturbance at near the low void fraction rate region.

Thus, by comparison of model experimental results with two-dimensionally visualized images of shaft pressures in an actual blast furnace, the condition of the charge near the furnace wall inside may be estimated.

5. Relationship between Shaft Pressure Fluctuation and Cohesive Zone Root Position

Inferring from the experimental results, the phenomenon of the uneven distribution of the shaft pressure may be due to the presence of a portion where the void fraction rate is higher or lower in the shaft. Specifically, it may be brought about by various causes including the accumulation of dust or deposits, and the degradation in the circumferential balance at the root of the cohesive zone. In the following subsections, our discussions are focused on the cohesive zone root as the cause. In other words, we are examining the relationship between the root position of the cohesive zone estimated by using two-dimensionally visualized images of the stave temperature, and the position where the shaft pressure fluctuation occurred.
5.1. Estimation of the Cohesive Zone Root Position

Many studies employing shaft pressure or stave temperature have been conducted on methods estimating the cohesive zone. The estimation by the two-dimensional visualization of images can use either the stave temperature or the shaft pressure distributions.

In the estimation using the stave temperature, time differential rates of stave temperature may be used for the estimation. Since the gas flow resistance is high in the cohesive zone, the gas passing through the cohesive zone does not necessarily plug flow, but often leaks partially. As a consequence, the stave temperature will locally vary in the position corresponding to the root of the cohesive zone. It is assumable, therefore, that a region where the stave temperature variation per unit time is large represents the root position of the cohesive zone.

In the estimation using the shaft pressure distribution, spatial differential rates of shaft pressure may be used for the estimation. Usually, the pressure drop in the cohesive zone is higher than that in the shaft. If the gas flow should be degraded by, for example, the constriction of the central gas flow or by the accumulation of dust, the gas flow will be comparatively well dispersed and uniform within the shaft. However, at the root of the cohesive zone, the gas flow will be released toward the upper of furnace because the flow resistance is too high there to permit an easy lateral dispersion of the gas, resulting in an abnormally high-pressure loss. In other words, the pressure rise owing to the gas release plays the role of a sensor to apparently indicate the presence of a cohesive zone. There is therefore, a possibility, of detecting the root position of a cohesive zone by the position of an abnormally high-pressure rise.

However, for the bosh where a cohesive zone is likely to take place, and where the number of pressure gauges installed is small in view of possible clogging, we estimated the root position of the cohesive zone by the rate of change over time of the stave temperature.

5.1.1. Cohesive Zone Root Level Estimation via the Stave Temperature

Contour charts were plotted to illustrate the time differential rates using the stave temperature distribution, with set up threshold values for the highest and lowest time differential rates, and cut out charts formed by the contour charts of the threshold values. The contours of the charts were divided into upper and lower curves in order to determine an average value, and the circumferential distributions of the top and bottom positions of the cohesive zone root were estimated.

In this estimation, a small-scale channeling in the vicinity of the cohesive zone is used as a means for detection. Therefore, if such a channeling does not occur, or if a large-scale channeling that originates from a zone other than the cohesive zone occurs, the location of the cohesive zone root cannot be estimated. So, an average cohesive zone area is estimated by placing root areas, one over another, which can be detected in a certain period of time, 8 h for instance. Such treatment will also serve to reduce the possibility of detection capacity degradation by adhering substances.

5.1.2. Example of the Cohesive Zone Root Level Estimation

An example of the estimation of the root zone of the cohesive zone is shown as thick full lines in Fig. 8. The upper and lower limits of the time differential rates of the stave temperature for determination of the cohesive zone were preset at ±0.2°C/min. The criteria for this determination generally need to be decided by considering the operating condition of the blast furnace and its current length of operation. It can be seen from Fig. 8 that a region presumable to be a level of root of the cohesive zone is partially determinable. By tracing this region in time sequence, the root level distribution of the cohesive zone and its time fluctuation are quantitatively determinable.

5.1.3. Comparison with Actual Measurement by a Vertical Probe

We can compare the calculation results with the measurements of a vertical probe in an actual blast furnace. Figure 9 shows a cohesive zone top level change of approx. 2 meters in two periods of A and B, and Fig. 10 indicates that the upper levels of the measured cohesive zone almost coincide with those obtained by the time differential rates of stave temperature.

5.2. Position Change of the Cohesive Zone Root When the Furnace Is Not in a Good Condition

We discussed above that shaft pressure fluctuations occur in a region where an abnormal rise and an abnormal drop of the spatial differential rates of shaft pressure take place in a pair, and that this occurs when the anomalies of the pressure have disappeared. A time sequence of the origins of such abnormal rises of the spatial differential rates of shaft
pressure shown in Fig. 11.

Figure 12 shows the upper and the lower root positions of the cohesive zone, estimated by the change in the stave temperature, also in a time sequence.

Figure 12 indicates that the upper root position of the cohesive zone almost constantly remains at levels approx. 5 meters above the tuyere until mid September, but from then, rose to about 8-meters.

From Fig. 11, we see that the high spatial differential rates of shaft pressure points, namely, the origins of the shaft pressure fluctuations, approximately correspond to the upper root positions of the cohesive zone, and that when the shaft pressure rose, the origins also rose. Thus, the positions of the origins of the shaft pressure fluctuations coincide with the cohesive zone root level fluctuations on the whole, denoting that the origins of the shaft pressure fluctuations are affected by the root level of the cohesive zone. In addition, we have another indication that, when the cohesive zone root level rose, slips also increased (see Fig. 13). This may be explained by the fact that the bubbling, which had remained in the depths of the furnace, rose up to the layer surface as the origins of the shaft pressure fluctuations rose to higher levels and had an effect on the descending path of the burden. The origins of shaft pressure fluctuations, however, concentrated in the bosh, suggest the presence of other influential factors in addition to the root level of the cohesive zone.

Thus, it is possible to quantitatively determine and analyze the occurrence of the cohesive zone root level fluctuations and shaft pressure variations by using two-dimensionally visualized images and their secondarily processed data.

6. Conclusion

By converting the stave temperature and shaft pressure data, collected by a number of sensors spatially located circumferentially and vertically within blast furnaces, into images distributed in two dimensions, we have succeeded in quantitatively and objectively visualizing the shaft pressure variations and spatial changes caused by slipping in blast furnaces. In addition, by combining the two-dimensional distribution of the secondarily processed data of changes in space and time with the progress of operation data, it enables early detection of shaft pressure fluctuations. The uneven distribution of voids in the blast furnace had been stipulated as the cause of shaft pressure fluctuations, and this has been confirmed by our model experiments. It has been
also determined that there exists a relationship between the cohesive zone root position, assumed by the visualized two-dimensional image of the stave temperature change over time, and the origins of the shaft pressure fluctuations.

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