Fully Automatic Blowing Technique for Basic Oxygen Steelmaking Furnace

By Yoshiharu IIDA,** Kanji EMOTO,*** Masakatsu OGAWA,*** Yasuo MASUDA,**** Masayuki ONISHI*** and Hiroseke YAMADA***

Synopsis
An innovative technique has been sought for slag formation control in LD converter in order not only to obtain a perfect simultaneous hitting of aimed carbon content and bath temperature but also to control phosphorus content at turndown.

The acceleration of oxygen lance vibration is found to be correlated with slag foaming height in the vessel. Through the introduction of continuous monitoring of the acceleration into existing programed and dynamic control subsystems, a fully automatic blowing system has been established.

Due to this innovation, significant benefits such as improvement in hitting ratio and yield of steel, reduction in reblowing ratio and longer refractory life have been achieved.

I. Introduction
More than twenty years have passed since the basic oxygen furnace entered the mainstream of the steelmaking process due to its high productivity and excellent quality. This converter steelmaking process has the drawback that just because of the high-speed blowing, one of its features, it is difficult to get a simultaneous hit of the target carbon content, molten steel temperature and phosphorus content at turndown.

The hitting ratio of the carbon content and molten steel temperature increased to 80% owing to the development of dynamic control techniques using a sub-lance. However, to obtain hitting ratio over 90% and control the phosphorus content, the problem of slag formation control has to be solved. Paying attention to the fact that the oxygen-blowing lance vibrates in response to slag formation, Kawasaki Steel Corp. has established a system for continuous monitoring and control of slag formation and as a result, it has succeeded in fully automating the blowing process.

II. Historical Progress of Development of Blowing Control Techniques
Figure 1 shows the historical progress of blowing control techniques at Kawasaki Steel Corp. To obtain hits of the carbon content and molten steel temperature, computer control has been operating since the introduction of the BOF using static control models based on the material balance and heat balance. Since the manipulated variables are determined only by the initial conditions of blowing in static control, there was a limit to the accuracy of end-point control.

To compensate for this drawback, the development of a dynamic control technique utilizing waste gas analysis was undertaken. But, there was a limit to the accuracy because the dynamic control was based on indirect measurement. Furthermore, temperature measurement had to be ascertained by other means, for example, throw-in type pyrometers. However, the reliability of throw-in pyrometers is low and the hitting ratio of the carbon content and molten steel temperature was as low as 45 to 50%.

To achieve a breakthrough, a fully automatic sub-lance was installed in June, 1974 which permits direct sampling and temperature measurement of the molten steel in the vessel during blowing. The simultaneous hitting ratio of the carbon content and molten steel temperature reached 80% owing to the development of measuring probes and the improvement of dynamic control models. However, variations in slag formation caused variations in the oxygen efficiency in the final stage of blowing and it was difficult to obtain simultaneous hitting ratios above 90%. In addition, dephosphorization control was increasingly required as the production of high-grade steels increased, and development of slag formation control techniques became urgent needs.

Attempts were made to estimate the foaming slag height by acoustic measurement or furnace vibration measurement, and to estimate the degree of slag oxidation by waste gas analysis, etc. However, these methods posed problems in terms of accuracy and response speed.

Therefore, programed blowing in which blowing is standardized was performed with a view to increasing the reproducibility of the reactions in the vessel. In this technique, the adjustment of the lance height, oxygen flow rate and flux charging from the start to the end of blowing are automatically performed if a blowing program is selected from combinations of initial conditions, (such as the hot metal ratio, chemical composition and temperature of hot metal), and end-point conditions, (such as target temperature, carbon content and phosphorus content at turndown, etc.) However, slag formation is not always constant even if blowing is performed with the same initial conditions, end-point conditions and blowing program, and it was impossible to completely eliminate intervention by the operator during blowing. Meanwhile, a tech-
technique for continuously estimating the foaming slag height by the measurement of the vibration of the oxygen-blowing lance was established and a fully automatic blowing system that covers the whole blowing process from the start to the end of blowing was completed by combining this technique with programed blowing.

### III. Composition of Fully Automatic Blowing Control System

As shown in Fig. 2, the fully automatic blowing control system is composed of the subsystems A to D.  

A: Subsystem for Static Control  
The raw material blending and amounts of oxygen, coolant and fluxes necessary for blowing are calculated using static control models based on the material balance and heat balance.

B: Subsystem for Program Control  
The lance height and oxygen flow rate are automatically controlled and fluxes are automatically charged according to the blowing program selected before blowing. This subsystem also controls the operation of the waste gas treatment system, the gas recovery operation and start of the sublance operation.

C: Subsystem for Slag Formation  
This subsystem continuously monitors slag formation based on the measured values of acceleration of lance vibration and controls the lance height and oxygen flow rate.

D: Subsystem for Dynamic Control by Sublance  
The molten steel temperature and carbon content are measured by the sublance during blowing and the required amounts of oxygen and coolant are calculated using dynamic control model, whereby the charging of the coolant and the stop of blowing are automatically carried out.

Table 1 gives the specification of the subsystem for programed blowing D. Blowing is performed automatically by selecting a blowing pattern according to initial conditions (hot metal ratio, temperature and composition of hot metal, furnace condition, etc.) and end-point conditions (target temperature and composition at turndown). An example of blowing pro-

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Fig. 1. Development of blowing control technique in BOF.

Fig. 2. System and function of fully automatic blowing.
grams is shown in Fig. 3. That is to say, programmed blowing is a kind of static control. The subsystem is for the dynamic control of the foaming slag height and automatically corrects the blowing pattern selected by the subsystem so that the ideal foaming slag height can be obtained.

**IV. Slag Formation Control System by Lance Vibration Measurement**

1. **Basic Principle of Slag Formation Monitoring**

About 80 to 120 kg of slag per ton of steel is formed in the vessel by blowing and the CO gas generated by the decarburizing reaction causes this slag to foam. If slag formation is insufficient the slag is hard and no foaming takes place. If conversely, slag is too fluid, excessive foaming takes place and eventually slopping occurs; that is, slag overflows from the mouth of the furnace.

As shown in Fig. 4, the lance receives the kinetic energy from the slag and vibrates when the slag reaches it, due to foaming. It was found that the foaming slag height can be estimated from the magnitude of the vibration.

2. **Lance Vibration Measuring Device**

Figure 5 shows the principle of the system for slag formation control. The lance is suspended with wires and can be vibrated with a lance clamping device as the support point. Since the natural frequency of the lance proper is low, a quartz oscillating accelerometer was adopted which is suitable for the measurement of changes in acceleration of low frequency. The direction of lance vibration is not constant. It changes gradually during blowing. Therefore, two accelerometers were arranged at right angles to each other and the composite acceleration was calculated.

Figure 6 shows output waveforms obtained from accelerometers in actual operation. Figure 7 shows the frequency spectrum of these waveforms. Results of frequency analysis reveal that the peak value is observed near the natural frequency of the lance, at 0.39 Hz, and that spectral intensity at any frequency increases with increasing foaming slag height.

3. **Relation between Lance Vibration and Foaming Slag Height**

The foaming slag height was intermittently measured during blowing using a sublance provided with a specially fabricated probe for bath level measurement, and was analyzed in terms of its relation to the acceleration of lance vibration. Results of this analy-
sis are shown in Fig. 8(a). The relationship given by Eq. (1) was observed among the oxygen flow rate, depth of lance immersed in slag and acceleration of lance vibration, \( G \).

\[
G = a F_{O_2} (S_H - L_H) + b \quad \text{(1)}
\]

where, \( G \): acceleration of lance vibration \((\text{cm/s}^2)\)
\( F_{O_2} \): oxygen flow rate \((\text{Nm}^3/\text{min})\)
\( S_H \): foaming slag height \((\text{m})\)
\( a, b \): constants.

To verify the validity of Eq. (1), a water model experiment was conducted using a 1/10 model of a 250-t converter. Air was injected through a lance with four-holes as in an actual converter, using a foaming liquid composed of aqueous solution of soap and polyethylene oxide (material to control viscosity). Figure 8(b) shows the results of this experiment. It was confirmed that the experimental results closely agree with Eq. (1).

In general, the force that acts on a cylinder placed in a liquid is given by Eq. (2):

\[
F = D \cdot L \cdot C_D \cdot (1/2 \rho \cdot U^2) \quad \text{(2)}
\]

where, \( D \): cylinder diameter
\( L \): immersion depth of the cylinder
\( C_D \): resistance coefficient
\( U \): flow velocity of the liquid
\( \rho \): density of the liquid.

If Eq. (2) is considered to represent a phenomenon in the converter, the resistance coefficient, \( C_D \), changes depending on the physical properties of slag. However, it might be thought that the resistance coefficient is almost constant unless slag basicity is abnormal. \( 1/2 \rho \cdot U^2 \) represents the oscillating energy of slag and relates to the deviated position of the kinetic energy of slag given by the ascending gas. It seems that the larger the volume of CO gas generated, the larger this oscillating energy of slag. If for simplicity, this oscillating energy of slag is considered to be proportionally related to the oxygen flow rate, \( F_{O_2} \), Eq. (2) supports the empirical Eq. (1), \((L = S_H - L_H)\).

4. Technique for Slag Formation Control

The principal aim of slag formation control is to prevent slopping and keep a suitable foaming slag height by correcting the lance height or oxygen flow rate, if the foaming slag height deviates from its proper range. As shown in Fig. 5, \( G \) obtained by the vector addition of \( G_x \) and \( G_y \) (acceleration of lance vibration measured by two accelerometers arranged at right angles to each other on the same level), lance height, \( L_H \), and oxygen flow rate, \( F_{O_2} \), are fed into a process computer every moment, and the foaming slag height, \( S_H \), is continuously calculated by Eq. (3) obtained by transforming Eq. (1):

\[
S_H = \frac{G + b}{a F_{O_2}} + L_H + B_H \quad \text{(3)}
\]

where, \( B_H \): term of furnace-bottom height correction.

In actual vessels, the furnace-bottom height changes due to the erosion of bottom refractories or adhesion of slag. Therefore, a factor for furnace-bottom height correction is incorporated in Eq. (3).

Figure 9 illustrates the concept of slag formation control.
control for each rank selected according to the \( S_h \)-value. When the judgment result is "good", the blowing pattern continues as programmed. Otherwise, the blowing program is adjusted for soft blow or hard blow and the initial program is followed after the judgment returns "good".

The boundary values of each rank were empirically determined using the result of dephosphorization as the evaluation index. However, the minimum height for the slopping region was fixed by measurements with a sublance.

When the action for slag formation control is done, the effect is appeared after tens of seconds. As shown in the example of control logic in Fig. 10, therefore, a kind of control with variable-interval sampling is adopted to compensate for this slag. Figure 11 shows an example of slag formation control in the 250-t BOF of Mizushima No. 2 Steelmaking Shop. Adjustments were made at the points of time indicated by arrows.

5. Relation between Foaming Slag Height and Dephosphorization

An investigation was made into the relationship between the foaming slag height and the turndown phosphorus content in a 250-t converter in order to verify whether slag foaming, a physical action, can be used as a control index for dephosphorization, a chemical reaction. As is apparent from Fig. 12, it was found that the higher the accumulated foaming slag height, the more dephosphorization is promoted. Thus it was ascertained that the foaming slag height can be used as an index representing the dephosphorizing capacity of slag.

V. Hardware of Fully Automatic Blowing Control System

Figure 13 shows the system configuration of fully automated blowing control. When a blowing program is selected and blowing is started, all the operating steps up to the end of the blowing are performed by the subsystems \( \mathbb{A} \), \( \mathbb{B} \) and \( \mathbb{C} \) shown in Fig. 2 based on direct outputs from the BOF process computer to the plant controllers. Moreover, the lance height and oxygen flow rate are adjusted by the subsystem for slag formation control \( \mathbb{D} \) and blowing process fully automatically.

VI. Results of Fully Automatic Blowing

Figure 14 shows the transition of blowing performance at the No. 2 Steelmaking Shop of Mizushima Works before and after the adoption of fully automatic blowing practice. The simultaneous hitting ratio of the carbon content and molten steel temperature at turndown reached 95% and the reblow ratio de-
creased remarkably. As a result, it became possible to perform a QDT (quick and direct tapping) operation, in which steel is tapped just after the end of blowing without having to make certain of the blowing results at turndown. The time required from the end of blowing to tapping could be substantially reduced as shown in Fig. 15. In addition, the yield of low-carbon rimmed steel increased by 0.5 to 1.0%, as shown in Fig. 16, due to the facts such as reduced slopping and reblowing, decrease in heat loss resulting from the shortened time required from the end of blowing to tapping and decrease in burnt lime consumption. Table 2 summarizes these results.

VII. Application to Top- and Bottom-blowing Converters

Since the announcement of excellent operation at results of Q-BOP, studies have been carried out to increase the stirring force of the steel bath by blowing gas from the furnace bottom and various types of top- and bottom-blown converters have begun operation. In top- and bottom-blown converters, in which a small volume of inert gas is blown, (LD-KGC process at Kawasaki Steel Corp.) the condition of slag foaming during blowing is not very different from that observed in LD converters. Therefore, this fully automatic blowing control system can be applied to top-

![Image of fully automatic blowing system hardware](image-url)
and bottom-blown converters without modifications.

In Kawasaki Steel Corp.'s K-BOP process, in which a large volume of oxygen (1.5 Nm³/min-t maximum) is blown from the bottom, slag foaming is far slighter than in top-blown converters and LD-KGC converters except at the end of desiliconization in the initial stage of blowing. However, as shown in Fig. 17, slopping may occur in the initial stage of blowing depending on the method for adding lumpy lime. This slopping can be monitored by the measurement of the lance vibration. Thus, this fully automatic blowing control has been used as an effective technique not only in top-blown converters, but also in top- and bottom-blown converters.

VIII. Conclusion

The fully automatic blowing technique for basic oxygen furnace using slag formation monitoring and control techniques by lance vibration measurement has made it possible to automate converter blowing at steelworks using a complex steel grade mix, which had up to this time been considered difficult. As a result, the accuracy of end-point control was improved and the performance of converter operation were greatly improved due to an improvement in the simultaneous hitting ratio of the carbon content and molten steel temperature at turndown, and a decrease in the time required from the end of blow to tapping etc.,

Table 2. Performance of automatic blowing.

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<thead>
<tr>
<th></th>
<th>Conventional</th>
<th>Fully automatic</th>
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<tbody>
<tr>
<td>Simultaneous hit ratio for C &amp; temp. at blow end (%)</td>
<td>47</td>
<td>95</td>
</tr>
<tr>
<td>Reblow ratio (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>For [P] &amp; [S]</td>
<td>15</td>
<td>3.5</td>
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<tr>
<td>Total</td>
<td>32</td>
<td>6.0</td>
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<tr>
<td>Time (blow end ~ tapping) (min)</td>
<td>8.5</td>
<td>2.5</td>
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<tr>
<td>Slopping heat ratio (%)</td>
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<td></td>
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<tr>
<td>Change of steel yield (%)</td>
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<td>0</td>
</tr>
<tr>
<td>Change of lime consumption (kg/t)</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Life of furnace (heats)</td>
<td>1 400</td>
<td>2 100</td>
</tr>
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REFERENCES