Development of Bottom-blowing Nozzle for Combined Blowing Converter*

By Hei-ichiro ISO,** Yutaka JYONO,** Keiji ARIMA,**
Michitaka KANEMOTO,** Masaki OKAJIMA*** and Hiroshi NARITA***

Synopsis

A bottom-blowing nozzle of a converter, being featured by a wide range of flow rate controllability and a low wearing rate, has been studied with the view of developing a top- and bottom-blowing converter which is capable of producing a wide variety of steel.

(1) When an inert gas is injected into the steel bath through the bottom-blowing nozzle, a so-called mushroom (solidified iron) having extremely small pores is formed atop the nozzle by the cooling effect of gas.

(2) When a stable mushroom is formed atop the nozzle, the flow rate controllability and the wear rate of the nozzle are improved.

(3) In order to form a stable mushroom atop the nozzle, it is most effective to use a nozzle consisting of multiple small-diameter pipes.

(4) There is a proper range for the diameter of individual pipes. On the basis of the heat transfer model it has been established that, for the specified diameter, there is the minimum value both for the distance between neighboring pipes and for the gas flow rate to form a stable mushroom atop the nozzle.

(5) This bottom-blowing nozzle allows to control the bottom gas flow rate over a wide range and ultimately makes it possible to control the iron content in slag (T.Fe) widely. In a low carbon region, the iron content can be reduced by bottom gas injection with the full flow rate. In a high carbon region, the nozzle can be used at a low gas flow rate to increase the iron content and ensure proper dephosphorization of the same level as in a top-blowing converter. Thus, this process is applicable for the production of all grades of plain carbon steel.

Key words: basic oxygen steelmaking; top- and bottom-blowing converter; bottom-blowing nozzle; flow rate controllability; mushroom.

I. Introduction

The recent progress of bottom-blowing converter processes (Q-BOP *etc.*)¹⁾ revealed that agitation of bath in top-blowing converter is insufficient. This recognition of insufficient bath agitation had led to the research and development of top- and bottom-blowing converter processes. For example, LD-OB process^{2,3)} which used oxygen and propane as its bottom gases was developed in 1980. This process solved the problem of insufficient bath agitation in top-blowing converters. It also improved the molten steel yield and reduced the ferroalloy consumption significantly through a decrease in total iron content of slag (T.Fe). In LD-OB process and the other top- and bottom-blowing converter processes using pure oxygen as bottom gas, bottom-blowing nozzles with relatively large aperture are used. Consequently, it is practically impossible to reduce the flow rate of bottom gas to avoid hot metal penetration into the nozzles or bubbles of injected gas striking at the nozzle top.⁴⁾ Thus, when the nozzle diameter is determined for a higher

gas flow rate to refine a low carbon steel, (T.Fe) becomes insufficient for refining of high carbon steel. Since inadequate (T.Fe) prevents desirable dephosphorization for some steel grades, those processes can only be applied to limited steel grades. In this connection, the authors sought for such a top- and bottom-blowing converter process having the refining characteristic of either bottom-blowing process (Q-BOP *etc.*) or top-blowing process depending on the steel grade, that can be applied to all steel grades. As a result, a new type of top- and bottom-blowing converter process which is able to use CO₂, N₂, Ar, *etc.* as its bottom-blown gas was developed (hereafter called LD-CB process).⁵⁾ The first LD-CB converter on a commercial basis was installed at Sakai Works, Nippon Steel Corp., in 1982. For this purpose, a new type of bottom nozzle, which is featured by a wide range of flow rate controllability and a low wearing rate, was developed. When the gas is injected into a converter through a bottom-blowing nozzle, a so-called mushroom^{6,7)} with extremely small pores is formed atop the nozzle by the cooling effect of the gas. The properties of this mushroom have significant effects on the nozzle flow rate controllability and the wear rate of the nozzle. A stable mushroom prevents direct contact of hot metal with the nozzle, hence the nozzle is not subject to heavy wear. Also, in this case, the bottom-blown gas continues to pass through a number of small pores in the mushroom, and the range of bottom-blown gas flow rate can be extended to lower level, as choking of the pores is avoided by the surface tension of molten iron.

In the following sections, the authors describe the development of the bottom-blowing nozzle which is capable of forming a stable mushroom, the conditions for mushroom formation and the bath agitating effect of the newly developed nozzle.

II. Experimental Method

1. Equipment and Nozzles Used for Experiments

The authors designed various types of bottom-blowing nozzles to improve the flow rate controllability and to reduce the wear rate. The characteristic of flow rate and the wear rate of these nozzles were determined by the experiments used an actual converter.

In the experiments, emphasis was placed on elucidation of the effects of the formation of mushroom on

* Manuscript received on May 14, 1987; accepted in the final form on September 11, 1987. © 1988 ISIJ

** Formerly Sakai Works, Nippon Steel Corporation. Now at R & D Laboratories-III, Nippon Steel Corporation, Edamitsu, Yahatahigashi-ku, Kitakyushu 805.

*** Sakai Works, Nippon Steel Corporation, Chikko-Yawatomachi, Sakai 590.

the controllability of nozzle flow rate and the reduction of wear rate of nozzle. Also, the authors studied the conditions of bottom gas flow rate and the type of nozzle for the formation of stable mushroom.

The experiments were done by the use of a 170-t converter of Sakai Works. The outline of the setup for the experiments is shown in Fig. 1. As the bottom-blown gas, either CO₂, N₂, or Ar was used at the maximum pressure of 25 kg/cm².

Figure 2 shows three types of nozzles used for the experiments. Those were designed on the basis of the following concepts.

The single-pipe nozzle shown in Fig. 2(a) was designed with emphasis on the simplification of nozzle shape. When an inert gas is blown through the nozzle, it is unnecessary to use a double-pipe nozzle, which is indispensable for oxygen blowing to inject cooling gas through the outer pipe.

The double-pipe nozzle shown in Fig. 2(b) was designed to reduce the flow rate of the gas through the inner pipe. The flow rate of the gas through the inner pipe can be reduced, when the flow velocity of the gas through the outer pipe slit is increased to the level to be able to prevent penetration of hot metal into the inner pipe.

If a single-pipe or a double-pipe nozzle having relatively large aperture is used, there is a fear of hot metal penetrating into the nozzle or bubbles of injected gas striking at the nozzle top. In this connection, the gas flow velocity at the nozzle outlet was maintained so as to be the supersonic level⁴⁾ during the run.

The nozzle consisting of multiple small-diameter pipes shown in Fig. 2(c) was designed to prevent penetration of hot metal into the nozzle by reducing

the cross-sectional area of individual pipe to increase the effect of surface tension, so that the minimum limit of flow rate can be reduced. Also, the nozzle consisting of multiple small diameter pipes was designed to form a stable mushroom which originated from many small-diameter pipes and stuck firmly atop the nozzle. In this connection, the authors studied the conditions required to the nozzle structure (the distance between neighboring small pipes and the diameter of small pipe *etc.*) to form a stable mushroom. Each of the nozzles mentioned above is made of stainless steel pipe embedded in refractory (MgO-graphite) and fitted in the tuyere block installed at the converter bottom.

2. Items Investigated and the Measuring Method

In the experiment, the gas flow rate and the pressure characteristic (P-Q characteristic) of each nozzle was measured by the use of a flowmeter and a pressure gauge installed in the pipe leading to the nozzle. The nozzle wear rate (mm/heat) was obtained by measuring the length of remaining nozzle periodically in the blowing operation with a laser profilometer (He-Ne laser, accuracy: $\sigma=5$ mm). The wear rate measured by a laser profilometer was confirmed by the figure of the recovered nozzle after the experiment. Temperature of each nozzle was measured by the thermocouple (CA-sheathed, 1.6 mm ϕ) embedded in the nozzle as shown in Fig. 2. The mushroom formation atop the nozzle was visually observed after tapping. Some mushrooms were recovered at the end of the experiment.

The chemical compositions of recovered mushrooms were determined by chemical analysis. Also, their inner structure was examined by X-ray photographs. The chemical compositions of the metal samples obtained through a sublance were analyzed with an emission spectroscopic analyzer and the compositions of the slag samples were analyzed with a fluorescent X-ray analyzer to examine the change in composition caused by agitation.

III. Experimental Results

1. Mushroom Formation

When the gas is injected into the converter through a bottom-blowing nozzle, a mushroom is formed atop

Fig. 1. Outline of setup for experiment.

the nozzle as hot metal came in contact with the nozzle top is cooled by the gas. When the single-pipe nozzle is used, the mushroom as shown in Fig. 3 is formed atop the nozzle. An analysis of a cross section of this mushroom shows small pores branching out from the nozzle outlet. A similar mushroom is formed when the gas is injected through the double-pipe nozzle.

When the gas is injected through the nozzle consisting of multiple small-diameter pipes, a large mushroom (hereafter called united mushroom) which covered the entire top area of the nozzle is formed. The profile of a longitudinal section across the center of the mushroom is shown in Fig. 4. A part of the section etched by nitric acid is shown in Fig. 5. The photograph shows that the outer part of the mushroom has a laminated structure. Figure 6 is an X-ray photograph of the mushroom. The photograph shows that the mushroom has a great number of small pores originated from the outlet of individual small-diameter pipes of the nozzle. However, some conditions should be satisfied to form such a united mushroom. Figure 7 shows the experimental results about the formation of a united mushroom related with the distance of neighboring small pipes of the nozzle and the bottom gas flow rate. As is evident from Fig. 7, to form a united mushroom, it is necessary that the flow rate of bottom gas is high enough and that the distance between neighboring pipes of multiple-pipe nozzle is narrow enough. In the other case, separated

small mushrooms are formed atop the individual small-diameter pipes of the nozzle.

Fig. 5. Section of united mushroom. (Etched in nitric acid)

Positions from which sample for composition analysis were taken (see Table 1)

A: position corresponding to small-diameter pipe

Fig. 6. X-ray photograph of united mushroom.

Fig. 3. Cross section of mushroom formed atop single-pipe nozzle.

Fig. 4. United mushroom formed atop multiple-pipe nozzle.

Fig. 7. United mushroom formation related with gas flow rate and distance between neighboring small-diameter pipes.

2. Characteristic of Bottom-blowing Nozzle Flow Rate

Figure 8 shows the flow rate characteristic of various nozzles. The figure shows fluctuations in the bottom gas flow rate during blowing under “pressure-constant control”. With a single-pipe or a double-pipe nozzle, the nozzle flow resistance increases and the gas flow rate decreases at As shown in Figs. 8(a) and 8(b). The nozzle flow resistance sometimes decreases and the gas flow rate increases during blowing at Bs shown in Figs. 8(a) and 8(b). In such a case, the disappearance of mushroom was observed visually after tapping. Thus, with a single-pipe or a double-pipe nozzle, the nozzle flow resistance sometimes increases and sometimes decreases. Namely, in the case of these types of nozzles, unstable mushrooms which appear and disappear from time to time, are formed and therefore, the nozzle flow resistance shows wide fluctuations. Consequently, the gas flow rate of nozzle becomes unstable.

With a multiple-pipe nozzle, the gas flow rate also decreases by the formation of a mushroom at A shown in Fig. 8(c). In this case, the increase in nozzle flow resistance by the mushroom formation is less than that with a single-pipe or a double-pipe nozzle (it is not more than 3 kg/cm², when the bottom-blown CO₂ flow rate is 500 Nm³/h). Also, in this type of nozzle, a united mushroom is formed and it is much more stable than that with a single-pipe or a double-pipe nozzle. It maintains its shape for a considerably long time so far as the flow rate of bottom gas is sufficient. The flow resistance of nozzle hardly fluctuates so far as a stable and united mushroom exists atop the nozzle at C shown in Fig. 8(c). Thus, in the case of multiple-pipe nozzle, the nozzle flow resistance remains virtually constant and the gas flow rate can be controlled accurately. Also, as the bottom-blown gas passes through small pores in the mushroom, hot metal does not penetrate into the pores because of surface tension. This makes it possible to change the flow rate of bottom-blown gas over a wide range. Figure 9 shows P-Q characteristic of a nozzle with multiple

Fig. 8. Flow rate characteristics of various nozzles.

small-diameter pipes.

3. Nozzle Wear Rate

Figure 10 shows wear of various nozzles with the elapse of time. With single-pipe and double-pipe nozzles, the amount of wear is sharply increased probably due to spalling. Their average wear rates are also fairly high; 2.7 to 6.2 mm/heat for the single-pipe nozzle and 2.7 to 6.6 mm/heat for the double-pipe nozzle. The multiple-pipe nozzle with stable mushroom shows an extremely low wear rate of 0.4 to 0.6 mm/heat. When a stable mushroom is not formed with the multiple-pipe nozzle, the wear rate becomes high, being 1.1 mm/heat as the average.

IV. Discussion

1. Selection of Nozzle with a Wide Range of Flow Rate Controllability

As already mentioned, when the gas is injected into hot metal through a bottom-blowing nozzle, a mushroom is formed atop the nozzle. This mushroom has the direct effect on the nozzle flow rate characteristic and the wear rate. With a single-pipe or a double-pipe nozzle, only an unstable mushroom is formed. It is impossible to control the bottom-blown gas flow rate constantly so far those mushrooms are dissolved or reformed time to time repeatedly.

After the experiment with a single-pipe nozzle, the

Fig. 9. Flow rate and pressure characteristics of multiple-pipe nozzle. (With mushroom)

Fig. 10. Wear rates of various nozzles.

mushroom was recovered and its permeability was studied. The mushroom showed considerable flow resistance. Minute pores in the mushroom allowed to pass only about one half of the gas flow which had been available during the experiment. This fact suggests that, during the experiment, about one half of the gas actually blown does not pass through the mushroom, but flows away through elsewhere. From this, the mechanism of mushroom formation and dissolution is considered to be the one shown in Fig. 11. That is, when a mushroom with considerable flow resistance is formed as shown in Fig. 11(a), the gas flow rate in the mushroom decreases and about one half of the gas supplied does not flow through the mushroom, but may flow through some other route, for example, between the mushroom and nozzle block. Therefore, the cooling of mushroom by the gas becomes insufficient, being responsible for the dissolution of mushroom as shown in Fig. 11(b), or for a gush of the gas around the mushroom, and for wear of the nearby refractories to such a degree that the mushroom is separated from the nozzle top as shown in Fig. 11(c). Eventually, the mushroom dissolves as shown in Fig. 11(d). Then, a mushroom begins to be formed again as shown in Fig. 11(e). In the meantime, the nozzle block is repeatedly exposed to thermal stress as a mushroom is alternately formed and dissolved, and this will cause spalling of the surface zone of nozzle block. It can be said that the substantial wear rate of single-pipe and double-pipe nozzles is due to the repetition of formation and dissolution of the mushroom as described above.

On the other hand, when a stable mushroom is formed with a multiple-pipe nozzle, the nozzle flow resistance remains virtually constant, and this allows to ensure stable gas flow. The effect of surface tension of molten iron is to prevent penetration of hot metal into the pores. Those serve to widen the range over which the gas flow rate can be varied. The increase in flow resistance due to the formation of the mushroom is less than that with the single-pipe or the

double-pipe nozzle. This is considered to be attributable to the fact that the gas is injected through a number of small-diameter pipes, hence many minute pores originating in the outlet of individual pipes are formed, and these supply the sufficient passage for the injected gas. Thus, with the multiple-pipe nozzle, the formation of a stable mushroom prevents direct contact of the nozzle with hot metal and hence reduces brick erosion. Also, the stable mushroom serves to reduce thermal stress applied repeatedly to the nozzle block and thereby it reduces the spalling. All those are considered to reduce the nozzle wear rate significantly.

From the above-mentioned considerations, it can be concluded that in order to improve the flow rate controllability of a bottom-blowing nozzle and to reduce wear of the nozzle, it is important to form a stable mushroom atop the nozzle and to use a nozzle consisting of multiple small-diameter pipes which is ideally suitable for the formation of a mushroom. The mechanism of the formation of a mushroom with the multiple-pipe nozzle is discussed below.

2. Mechanism of Formation of Stable Mushroom

In principle, the formation of a mushroom depends on the balance between cooling by the injected gas and heat transfer from hot metal. Here, the formation of a mushroom was studied as a heat-transfer phenomenon.

Table 1 shows the result of a chemical analysis of the parts of a stable mushroom shown in Fig. 6. The inner part of the mushroom has high carbon content of about 2.0 %, while the outer part consists of many layers with the carbon content of about 0.1 %. This facts suggests that the mechanism of mushroom formation with a multiple-pipe nozzle is as follows.

Around the middle of blowing (the carbon content of hot metal is about 2.0 %) of the heat right after installment of a new nozzle, a small primary mushroom is formed atop each of the small-diameter pipes as shown in Fig. 12(a). These small mushrooms grow to unite with one another as shown in Fig. 12(b). After this time, the specific surface area of each small mushroom decreases and the heat transferred from hot metal decreases, being allowed the continuous growth of the mushroom as shown in Fig. 12(c). Eventually, they form a stable and united mushroom

Table 1. Chemical compositions of stable mushroom.

Position	Element (%)				
	C	Si	Mn	P	S
Central part	1.86	0.01	0.16	0.050	0.012
Outer part	0.10	0.01	0.11	0.009	0.007

Fig. 12. Scheme of growth of stable mushroom.

Fig. 11. Estimated mechanism of mushroom formation and dissolution.

as shown in Fig. 12(d). It is considered that the stable mushroom is maintained while small portion of its outer layer dissolve or grow depending on the heat balance between cooling by gas and heat transfer from hot metal.

Figure 13 shows the change in flow resistance of nozzle with the elapse of time during the blowing of first three heats after installment of a new nozzle. In the first heat, the flow resistance begins to increase from the middle of blowing. It is understood that at this time, many primary mushroom begin to form by the above-mentioned mechanism. In the third heat, the flow resistance is almost stabilized, suggesting the formation of a stable mushroom.

3. Mushroom Stabilizing Technology

1. Conditions for Formation of Stable Mushroom

As already mentioned, a stable mushroom is formed when small primary mushrooms grow and unite with one another and grow continuously as its specific surface area receiving heat from hot metal decreases. Here, the authors describe the condition (the diameter of individual pipe and the distance between neighboring pipes) required to form a stable and united mushroom. A heat-transfer model is used for the calculation.

(1) Heat-transfer Model on Formation of Stable Mushroom

It is assumed that small primary mushrooms formed atop the individual small-diameter pipes are of hemispheric shape (radius: r) having minute pores. The radius of each small mushroom (r) can be calculated by the use of the following heat-transfer model.

From the balance between heating by hot metal and cooling by gas, the following equation is obtained;

$$H_m \cdot 2\pi r^2 \cdot T_s = C_p \cdot F' (T_g^0 - T_g^i) \dots\dots\dots (1)$$

Heat transfer from mushroom to gas in minute pores of mushroom is expressed by the following equation;

$$\begin{aligned} C_p \cdot F' (T_g^0 - T_g^i) &= \int_0^r h_m \cdot (T_m - T_g) l dx \\ &\doteq h_m \left(\frac{T_m^0 + T_m^i}{2} - \frac{T_g^0 + T_g^i}{2} \right) l \cdot r \end{aligned} \dots\dots\dots (2)$$

From Eqs. (1) and (2), r is expressed by the following equation;

$$\begin{aligned} r &= -\frac{C_p F'}{h_m l} \\ &+ \sqrt{\left(\frac{C_p F'}{h_m l} \right)^2 + \frac{C_p F'}{2\pi H_m T_s} (T_m^0 + T_m^i - 2T_g^i)} \\ &\doteq \sqrt{\frac{C_p F'}{2\pi H_m T_s} (T_m^0 + T_m^i - 2T_g^i)} \dots\dots\dots (3) \\ &\because \left(\frac{C_p F'}{h_m l} \right)^2 \ll \frac{C_p F'}{2\pi H_m T_s} (T_m^0 + T_m^i - 2T_g^i) \end{aligned}$$

where, C_p : gas specific heat (kcal/Nm³°C)
 F' : gas flow rate per small-diameter pipe (Nm³/h)

Fig. 13. Change in nozzle flow resistance.

- H_m : coefficient of overall heat transfer between hot metal and mushroom (kcal/m²h° C)
- h_m : coefficient of overall heat transfer between mushroom and gas (kcal/m²h° C)
- l : total length of circumferences of minute pores in the individual primary mushroom (m)
- r : radius of mushroom (m)
- T_g : gas temperature (°C)
- T_g^0, T_g^i : gas temperature at the surface of mushroom, gas temperature at the inlet of minute pore (°C)
- T_m : mushroom temperature (°C)
- T_m^0, T_m^i : mushroom surface temperature, mushroom core temperature (°C)
- T_s : hot metal super heat (°C)
- x : distance from the center of mushroom (m).

In order to form a stable mushroom, it is necessary that small primary mushrooms formed atop the individual small-diameter pipes unite with one another. To this end, a half of the distance between neighboring pipes must be less than the mushroom radius (r).

The following assumptions were made for the calculation of Eq. (3). The coefficient of heat transfer between hot metal and the mushroom (H_m) is assumed to be 10⁴ kcal/m²h° C on the basis of the result of the study made by Ariyoshi *et al.*⁽⁸⁾ on heat transfer between hot metal and scrap in a converter. The coefficient of heat transfer between the mushroom and the gas (h_m) can be expressed by the following equation⁽⁹⁾ if it is assumed that the gas flow in mushroom minute pore is a turbulent flow.

$$h_m = \lambda / de \cdot N_u, N_u = 0.023 Re^{0.8} Pr^{0.4} \dots\dots\dots (4)$$

where,

$$V' = F' \cdot \frac{1}{273} \left(\frac{T_g^i + T_g^0}{2} + 273 \right) / \left(\frac{\pi}{4} de^2 \cdot N' \right) \dots\dots\dots (5)$$

Gas temperature at the surface of mushroom (T_g^0) can be expressed, from Eq. (1), as follows.

$$T_g^0 = \frac{2\pi H_m T_s r^2}{C_p F'} + T_g^i \dots\dots\dots (6)$$

- where, λ : heat conductivity of gas (kcal/mh° C)
- de : diameter of mushroom minute pore (m)
- N' : number of minute pores in individual primary mushroom
- Pr : Prandtl number of gas (—)
- Re : Reynolds number of gas (—)

V' : gas flow velocity in mushroom minute pore (m/h).

It is assumed that the stable and united mushroom and each small primary mushroom have the same figure of minute pore diameter ($d_e=0.3$ mm from the results of an analysis of the recovered mushroom). The number of minute pores in a small primary mushroom (N') is treated as a parameter because it can not be measured. The value of this parameter is determined on the basis of the data obtained about the marginal formation of a stable and united mushroom. Also, it is assumed that mushroom surface temperature is 1200°C on the assumption that the surface of the mushroom is maintained at the solidus temperature of hot metal (the carbon content is about 2.0 %), and that mushroom core temperature is 400°C from the actual nozzle temperature measured. Gas temperature at the inlet of minute pore is assumed to be 250°C .

On the above-mentioned assumptions, the radius of a small primary mushroom related to gas flow rate per small-diameter pipe is obtained. The bottom-blown gas used is CO_2 , whose properties are shown in Table 2. They are obtained on the assumption that the gas temperature is 800°C which is the average value of T_g^i and T_g^0 . Figure 14 shows the radius of small mushroom (solid lines) calculated from the number of minute pores in the mushroom as a parameter. As is evident from Fig. 14, the calculated radius of small primary mushroom (r) is nearly proportional to the square root of gas flow rate per small-diameter pipe. As already mentioned, in order to

Table 2. Physical properties used to calculate mushroom radius.

Gas type		CO_2	N_2	Ar
Coefficient of overall heat transfer between hot metal and mushroom	$H_m \left(\frac{\text{kcal}}{\text{m}^2\text{h}^\circ\text{C}} \right)$	10^4	10^4	10^4
Coefficient of overall heat transfer between mushroom and gas	$h_m \left(\frac{\text{kcal}}{\text{m}^2\text{h}^\circ\text{C}} \right)$	7.3×10^3	5.3×10^3	4.1×10^3
Gas specific heat	$C_p \left(\frac{\text{kcal}}{\text{Nm}^3^\circ\text{C}} \right)$	0.59	0.36	0.22

Fig. 14. Calculated radius of small primary mushroom.

form a stable and united mushroom, it is necessary that a half of the distance between neighboring small-diameter pipes is equal to or less than r . Therefore, the distance between neighboring pipes must be reduced at the lower gas flow rate operation. The data on the formation of stable and united mushroom during the actual operation (as shown in Fig. 7) also shows the same tendency.

(2) Conditions of Nozzle Required for the Formation of Stable Mushroom

Based on the calculation results mentioned above, the conditions of a nozzle (the diameter of individual pipe and the distance between neighboring pipes) required for the formation of a stable mushroom have been studied.

It is assumed that the number of small-diameter pipes is varied so that the P-Q characteristic of entire nozzle remains unchanged even when the diameter of individual pipe is changed. The flow resistance of small-diameter pipe of the nozzle can be expressed by the following equation;

$$P = \lambda \frac{L}{d} \cdot \frac{V^2}{2g} \propto \frac{L}{d} \left(\frac{F'}{d^2} \right)^2 = \frac{L}{d} \left(\frac{F/n}{d^2} \right)^2 \propto \frac{1}{d^5 n^2} \quad \dots\dots\dots(7)$$

where, d : diameter of small pipe (m)
 F : gas flow rate of entire nozzle (Nm^3/h)
 F' : gas flow rate per small-diameter pipe (Nm^3/h)
 L : length of small-diameter pipe (m)
 n : number of small-diameter pipes
 V : gas flow velocity in small-diameter pipe (m/h).

On the assumption that the nozzle P-Q characteristic is invariable, the right-hand side of Eq. (7) becomes constant, hence the following equation is obtained;

$$n \propto (1/d)^{5/2} \quad \dots\dots\dots(8)$$

If it is assumed that F is constant and that the radius of small primary mushroom is nearly proportional to the square root of F' from the former calculation, the following equation is obtained;

$$r \propto (F')^{1/2} = \left(\frac{F}{n} \right)^{1/2} \propto \left(\frac{1}{n} \right)^{1/2} \quad \dots\dots\dots(9)$$

In order to form a stable and united mushroom, the value of $D/2$ must be smaller than the radius of small primary mushroom. Namely, the diameter of each pipe of the nozzle and the distance between pipes must meet the following condition. The minimum distance between pipes is proportional to the 5/4-th power of the pipe diameter.

$$D/2 \leq r \propto (1/n)^{1/2} \propto (d^{5/2})^{1/2} = d^{5/4} \quad \dots\dots\dots(10)$$

where, D : distance between neighboring small-diameter pipes (m).

2. Conditions for Maintenance of Stable Mushroom

It is considered that the maintenance of the mushroom depends on the balance between cooling by gas and heat transfer from hot metal. In the actual op-

eration, 150~200 Nm³/h of CO₂ or 450~500 Nm³/h of Ar is found to be necessary to maintain the mushroom up to the end of refining, when thermal load becomes the largest.

In this connection, the phenomenon can be analyzed on the basis of the heat-transfer model.

(1) Calculation of Radius of a Stable and United Mushroom

If it is assumed that a stable and united mushroom is of hemispheric shape, and if the heat balance of the entire mushroom is taken into calculation, the radius of the stable and united mushroom can be expressed by the following equation, which is essentially the same as Eq. (3).

$$R = -\frac{C_p F}{h_m l} + \sqrt{\left(\frac{C_p F}{h_m l}\right)^2 + \frac{C_p F}{2\pi H_m T_s} (T_m^0 + T_m^i - 2T_g^i)} \div \sqrt{\frac{C_p F}{2\pi H_m T_s} (T_m^0 + T_m^i - 2T_g^i)} \dots\dots\dots(11)$$

where, $\mathcal{N}$: number of minute pores in the stable and united mushroom

R : radius of stable and united mushroom (m).

In calculations of Eq. (11), the values of variables are determined on the basis of the same assumptions as made in calculations of the radius of a small primary mushroom. However, the number of minute pores in a stable and united mushroom (N) is assumed to be about 2 000 from the result of analysis of recovered mushroom. Also it is assumed that the mushroom surface temperature is 1 500°C corresponding to the solidus temperature of hot metal at the end of blowing. On the assumptions, the radius of a stable and united mushroom is calculated for each gas and gas flow rate. Physical properties used for the calculations are shown in Table 2. The calculated stable mushroom radii are shown in Fig. 15.

The results indicate that the radius of the mushroom varies in accordance with the type of bottom-blown gas, and is nearly proportional to the square

Fig. 15. Relationship between bottom-blown gas flow rate and calculated radius of stable mushroom.
(Hot metal superheat = 150°C)

root of gas flow rate. Also, for various types of bottom-blown gas, the flow rate required to obtain a particular mushroom radius is calculated, and from the calculated values the capacity of each gas to cool the mushroom is determined. The results are shown in Table 3, with the cooling capacity of CO₂ expressed as 1.0.

(2) Comparison of Calculation Results with Experimental Ones

In order to determine the difference in cooling capacity between different types of gas, bottom gas was switched from CO_2 to N_2 during the blowing (see Fig. 16), and the change in nozzle temperature was measured, since it was considered that the thermal load by hot metal on the nozzle may vary with the change in mushroom size caused by the difference in cooling capacity among different types of gas. The experimental result is shown in Table 4. The table shows the nozzle temperature difference by the replacement of CO_2 with N_2 . The temperature does not change by the replacement in case that 1.0 part of CO_2 is replaced with 1.6~1.8 parts of N_2 . This means that the cooling capacity of CO_2 is 1.6~1.8 times as large as that of N_2 , and corresponds well to the calculation result shown in Table 3.

As the next step, the gas flow rate required to maintain a stable and united mushroom is calculated for different types of gas and different levels of hot metal temperature. The calculated result was compared with the experimental data for the formation of a stable and united mushroom in an actual converter. Figure 17 shows the calculation result, together with the relationship between the flow rate of bottom-blown gas and the formation of a stable and united mushroom. Figure 17 shows that in case of hot metal with higher superheat, the calculated marginal gas

Table 3. Mushroom cooling capacity of various gases.

Gas type	CO ₂	N ₂	Ar
Cooling capacity* ¹	1.0/1.0	0.6/0.6 ~0.7	0.4/—* ³
Minimum flow rate* ² to maintain stable mushroom (Nm ³ /h)	200/150 ~200	320/—* ³	550/400 ~550

*1 Calculated/Actual

*3 Not examined

*2 Hot metal superheat = 150°C

Fig. 16. Change in nozzle temperature when gas type is changed.

Table 4. Change in nozzle temperature by the replacement of CO₂ with N₂.

N ₂ flow rate (CO ₂ flow rate expressed as 1.0)	1.0	1.6	1.8	2.0	2.6
Nozzle temperature change	Increase	No change	No change	Decrease	Decrease

Fig. 17. Gas flow rate required to maintain stable mushroom.

Fig. 18. Relationship between [C] of hot metal and (T.Fe) in slag at turn-down.

Fig. 19. Relationship between turn-down [C] and (T.Fe) in slag. (High carbon region)

flow rate is higher in a linear relationship. This tendency corresponds well to the relationship between the gas flow rate and mushroom formation in an actual converter.

The calculation results are summarized in Table 3. If it is judged from heat transfer to a mushroom, the cooling capacity of N₂ and Ar are 0.6 and 0.4, respectively, with the cooling capacity of CO₂ as 1.0. These figures correspond well to the actual ones. Also, the calculated gas flow rate required to maintain a stable and united mushroom is 200 Nm³/h for CO₂ and 550 Nm³/h for Ar, corresponding well to 150 to 200 Nm³/h for CO₂ and 400 to 550 Nm³/h for Ar observed in an actual converter.

3. Effects of Bath Agitation by Bottom-blowing

The conditions to obtain the nozzle with higher flow rate controllability helped by the stable mushroom were made clear. The following describes the effect of bath agitation by bottom-blowing with the nozzle which offers a wide range of flow rate control with stable mushroom.

Figure 18 shows the relationship between the carbon content in molten steel and iron content in slag in a low carbon region at the CO₂ flow rate of 0.09 Nm³/(min.t) and Ar flow rate of 0.09 Nm³/(min.t). As is evident from Fig. 18, with a given turn-down carbon content, bottom-blowing reduces the iron content in slag. This is considered to be due to the bottom-blown gas, which intensifies bath agitation and promotes the reaction between molten steel and slag, bringing about a quasi-equilibrium state. And also, it is evident from Fig. 18 that the bath agitating effect of CO₂ is about 1.5 times as large as that of Ar. This is due to the increase in gas volume by the reaction of CO₂ and carbon in molten steel as follows.

In the blowing of high carbon steel, on the other hand, it is necessary to restrain bath agitation so as to facilitate dephosphorization.¹⁰⁾ Figure 19 shows the relationship between the turn-down carbon content in molten steel and the iron content in slag obtained when high carbon steel is blown. The data in Fig. 19 is obtained by reducing the flow rate of CO₂ down to 0.02 Nm³/(min.t). There is no difference between the iron content in slag by this process and that by the top-blowing process. Namely, by varying the flow rate of bottom-blown gas, it is possible for the process to produce high carbon steel as does the top-blowing converter process. Thus, with this process, whose bottom-blowing nozzle permits the gas flow rate to be varied over a wide range, it is possible to produce a wide variety of steel grades, from low carbon to high carbon steel, by adjusting the amount of bottom-blown gas during blowing opera-

Fig. 20. Relationship between (T.Fe) in slag and flow rate bottom-blown gas in LD-CB/LD-OB processes.

tion.

Figure 20 shows the change in iron content in slag when the flow rate of bottom-blown gas is varied. As is evident from Fig. 20, with a given carbon content, the phosphorus content and temperature range at turn-down, the iron content in slag decreases when the flow rate of bottom-blown gas is increased. It is necessary to keep the iron content at or above a certain level in order to ensure proper dephosphorization. Once the flow rate of bottom-blown gas exceeds the certain limit, it will be necessary to adjust the top-blowing conditions to secure the required iron content. This suggests that there is a critical flow rate of bottom-blown gas at which the bath can be agitated most efficiently. The critical flow rate is 0.05 to 0.06 $\text{Nm}^3/(\text{min}\cdot\text{t})$ for CO_2 and 0.08 to 0.09 $\text{Nm}^3/(\text{min}\cdot\text{t})$ for Ar. The difference between CO_2 and Ar is due to the reaction of CO_2 and carbon in molten steel mentioned above.

Because of the relationship between the flow rate of bottom-blown gas and metallurgical effect, this LD-CB process, using relatively small amount of bottom-blown gas, offers a metallurgical characteristic comparable to those obtainable with LD-OB or other top- and bottom-blowing converter using a substantial amount of pure oxygen as its bottom-blown gas even for refining of low carbon steel (see Fig. 20).

V. Conclusion

With a view to develop the top- and bottom-blowing converter process which is capable of producing a wide variety of steel grades ranging from low carbon to high carbon steel, the authors made research and development of a bottom-blowing nozzle featuring with a wide range of flow rate control and reduced the wear rate. As a result, the following points were made clear.

(1) It is important to form a stable mushroom atop the nozzle in order to improve the flow rate controllability and reduce the nozzle wear.

(2) In order to form a stable mushroom atop the nozzle, it is most effective to use a nozzle consisting of multiple small-diameter pipes.

(3) It is considered that a stable mushroom is formed by the following processes.

(i) A stable and united mushroom is formed by uniting of small primary mushrooms which are formed atop the individual small-diameter pipes of the nozzle in the middle of the first blowing operation for the new nozzle. Thereafter, the mushroom is kept stable except that its outer part grows or dissolves according to the heat balance.

(ii) With a multiple-pipe nozzle, in order for small mushrooms atop the individual pipes to unite with one another to form a stable mushroom, the diameter of each pipe and the distance between neighboring pipes must meet certain conditions. The minimum distance between pipes is proportional to the 5/4-th power of the pipe diameter.

(iii) The flow rate of bottom-blown gas required to maintain a stable and united mushroom has lower limit set by the heat balance on the mushroom. The lower limit depends on the type of bottom-blown gas and the superheat of hot metal. It is 150 to 200 Nm^3/h for CO_2 and 400 to 550 Nm^3/h for Ar.

(4) With this top- and bottom-blowing process using the nozzle capable of forming a stable and united mushroom, it is possible to control the iron content in slag widely because the flow rate of bottom-blown gas can be purposefully varied over a wide range. In a low carbon region, the iron content in slag can be reduced, while in a high carbon region the flow rate of bottom-blown gas has to be reduced to ensure proper dephosphorization as in a top-blowing converter. Thus, this process is applicable to all grades of plain carbon steel.

(5) This process offers satisfactory metallurgical effects even when the flow rate of bottom-blown gas is relatively low. For example, a flow rate of 0.05 to 0.06 $\text{Nm}^3/(\text{min}\cdot\text{t})$ (in the case of CO_2 blowing) or 0.08 to 0.09 $\text{Nm}^3/(\text{min}\cdot\text{t})$ (in the case of Ar blowing) yields sufficient metallurgical effects for low carbon steel.

REFERENCES

- 1) M. Kawana, K. Nakanishi, A. Okazaki, J. Nagai, J. Katsuki, S. Tanaka, K. Komamura and S. Yamada: *Tetsu-to-Hagane*, **64** (1978), S166.
- 2) T. Kai, H. Nakagawa, M. Hirai, S. Murakami, M. Nakajima and H. Araki: *Tetsu-to-Hagane*, **66** (1980), S235.
- 3) N. Moritama, S. Murakami, M. Okimori, A. Shinkai, H. Aoki and R. Sakomura: *Tetsu-to-Hagane*, **67** (1981), S875.
- 4) Y. Ozawa, K. Mori and M. Sano: *Tetsu-to-Hagane*, **65** (1979), S644; *Trans. Iron Steel Inst. Jpn.*, **20** (1980), B312.
- 5) H. Iso, Y. Jyono, M. Honda, K. Arima, M. Kanemoto and Y. Ueda: *Tetsu-to-Hagane*, **69** (1983), S1012; *Trans. Iron Steel Inst. Jpn.*, **24** (1984), B173.
- 6) H. Nakamura, K. Saito, T. Nozaki, K. Suzuki, H. Oonuma and T. Emi: *Tetsu-to-Hagane*, **67** (1981), S873.
- 7) T. Ibaraki, M. Okajima, Y. Ueda, M. Kanemoto and K. Arima: *Tetsu-to-Hagane*, **71** (1985), S175; *Trans. Iron Steel Inst. Jpn.*, **25** (1985), B247.
- 8) T. Ariyoshi, H. Mori, K. Tanizawa and M. Yamate: *Seitetsu Kenkyu*, (1969), No. 266, 95.
- 9) W. D. McAdams: *Heat Transmission*, 3rd ed., McGraw-Hill, New York, (1954), 219.
- 10) K. Taguti, M. Hanmyo, Y. Shirotani, T. Hasegawa, Y. Tamura and Y. Miyashita: *Nippon Kokan Tech. Rep.*, (1982), No. 95, 13.