Effect of Lance Design on Jet Behavior and Spitting Rate in Top Blown Process

Yoshihiko HIGUCHI and Yukari TAGO

Corporate Research & Development Laboratories, Sumitomo Metal Industries, Ltd., Ooaza-Sunayama, Hasakimachi, Kashima-gun, Ibaraki-ken 314-0255 Japan.

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It is important to know the behavior of jets from a top-blown lance in order to control the spitting phenomena in the converter. However, there are few studies on the characteristics of jets from nozzles and effects of them on spitting rates.

In this study, the characteristics of jets from multi-hole lance and the effects of them on spitting behavior were investigated by cold and hot model experiments. Furthermore, lances were proposed and evaluated which have newly designed 6-hole nozzles with different diameters and inclination angles.

As a result, spitting rates were found to be influenced by maximum dynamic pressure of jets and distance of pressure peak from the lance axis. And lances with newly designed nozzle arrangement were confirmed to be effective to decrease the spitting rate.

KEY WORDS: converter; lance; nozzle; jet; spitting; inclination angle; dynamic pressure.

1. Introduction

In steelmaking processes such as BOF and combination blowing, oxygen is supplied to the molten iron through nozzles in the form of a gas jet for decarburization. The gas jet tears off the liquid and generates droplets. These phenomena are generally referred to as “spitting” or “splash”. They are causes of operational problems and lead to lower productivity and lower metallic recovery in commercial plant. Therefore, it is necessary to suppress formation of the droplets and reduce “spitting” or “splash” by designing nozzles of the lance.

In many experiments,\textsuperscript{1–7} it is reported that the critical condition for spitting formation depends on cavity depth and surface tension and that spitting rate can be represented as a function of jet momentum or cavity depth. These experiments are carried out using single-hole lances, whereas recent converters are operated invariably using multi-hole lances with appropriate nozzle inclination. Experiments of multi-hole lances were carried out by Mori \textit{et al.}\textsuperscript{8} and it was reported that spitting rate increases with an increase in overlap ratio of hot spot which is defined by geometrical arrangement in multi-hole lances. However, they paid no attention to the real characteristics of the jets.

In this study, the characteristics of jets from multi-hole lances were investigated and their effects on spitting rate were clarified by cold and hot model experiments. Furthermore, newly designed 6-hole lances with different diameters and inclination angles adjacentlly were proposed and evaluated.

2. Experimental Apparatus and Procedure

2.1. Cold Model Experiments

Cold model experiments were carried out with a water model shown in Fig. 1 using compressed air on behalf of oxygen gas in commercial converters. The cylindrical vessel was made of acrylic resin with an inner diameter of 500 mm and a height of 1 100 mm. It was filled with tap water to the 195 mm level from the bottom. The compressed air was blown to the bath surface from the nozzle of the top lance for a period of 120 s. Gas flow rate and lance height were set to be $1.4 \times 10^{-2}$ m$^3$ (normal)/s and 200 mm, respectively. Impinging jets from nozzles generated water droplets on the bath surface and the droplets rose through the vessel. Spitting weight was measured as a weight of total droplets trapped in absorbent cotton which was set inside the vessel at heights of 400 to 900 mm from bath surface. Spitting rate was obtained by dividing the spitting weight by blowing time and area of absorbent cotton.
The radial distribution of the dynamic pressure of the jet was measured with a Pitot tube which was set as shown in Fig. 2. The pressure outputs of the tube were transformed into voltage signals, converted into digital signals and finally stored in the memory of a personal computer. The measured pressures were time-averaged to cancel the errors resulting from the fluctuation.

Multi-hole lances were used to clarify the effect of the radial distribution of jet pressure on the bath surface on spitting rate. Nozzle arrangements of the lances including (a) 4-hole type and (b) 6-hole type were shown in Fig. 3. In (a) 4-hole type, all nozzles had the same inclination angle of 10 or 15 degrees and the same nozzle diameter of 4.8 mm. On the other hand, in (b) 6-hole type, nozzles had different inclinations of 12 and 24 degrees for adjacent nozzles9) to avoid overlap between jets and had different diameters, $D_{12°}$ and $D_{24°}$. The diameters $D_{12°}$ and $D_{24°}$ represent nozzle diameters for the corresponding inclination angles, respectively. Ratio of nozzle diameters, $D_{24°}/D_{12°}$, was changed from 0.7 to 2.0. Each lance was fabricated from brass material and total nozzle exit area for each lance was set to the same value of 72 mm$^2$. The lance diameter was 45 mm and the distance between nozzle and lance center was 10 mm.

### 2.2. Hot Model Experiments

Decarburization experiments were conducted using a 1.7×10$^3$ kg-scale converter. The inner diameter and the height of the converter were 1 000 and 2 020 mm, respectively. Pig iron of 4.2 to 4.5% C, 0.01 to 0.05% Si, 0.35 to 0.45% Mn, 0.02 to 0.03% P was poured into the converter to the level of 310 mm from the bottom. Alloys and fluxes were not charged to avoid disturbing spitting behavior. The hot metal was stirred with bottom blowing argon gas of 8.3×10$^{-3}$ Nm$^{-3}$/s. Oxygen gas of 0.1 Nm$^{-3}$/s was blown through the nozzle of the top lance at the height of 400 mm from metal surface. Sampling boxes were set at the heights of 600 to 1 600 mm from the metal surface inside the converter to collect metal droplets torn off from the surface as earlier literature9). Sampling was carried out for 30 s three times for each heat and the averaged value was evaluated as the spitting collection rate.

Decarburization experiments were carried out only with 6-hole lances which had different inclination angles of 12 and 24 degrees for adjacent nozzles because the 6-hole lances showed a lower spitting rate than the 4-hole lances based on the results of cold model experiments. Convergent-divergent type (Laval type) nozzles were used and the throat diameters, $D_{12°}$ and $D_{24°}$, for two inclination angles were chosen so as to vary the ratio of $D_{24°}/D_{12°}$ from 1.0 to 1.38. Total area of nozzle throats for each lance was set to be equal to 137 mm$^2$. The nozzle throat diameters of the lances are listed in Table 2. The lance diameter was 89 mm and the distance between nozzle and lance center was 15 mm. The radial distributions of the jet pressure were also measured in the same method as cold model experiments to clarify their effects on the spitting collection rate.

### 3. Results of Experiment

#### 3.1. Spitting and Jet Behavior in Cold Model Experiments

The measured spitting rates in cold model experiments were plotted against the sampling height for 4-hole lances as shown in Fig. 4. The 4-hole lance with inclination angle of 15 degrees showed the lower spitting rates than that with inclination angle of 10 degrees. The measured spitting rates for the 4-hole lances were also plotted against the sampling height as shown in Fig. 5. The spitting rates for the 6-hole lances except for $D_{24°}/D_{12°}=0.7$ showed the lower value than those for the 4-hole lances. The spitting rate decreased with an increase in the sampling height in any conditions. The spitting rates at sampling height of 600 mm, $S_{\text{cold}}$ (kg/m$^2$·s), were plotted against the nozzle diameter ratio, $D_{24°}/D_{12°}$, as shown in Fig. 6. The spitting rate, $S_{\text{cold}}$, showed

| Table 1. Nozzle diameters of 6-hole lances for cold model. |
|-----------------|-----------------|-----------------|
| $D_{12°}$ (mm)  | $D_{24°}$ (mm)  | $D_{24°}/D_{12°}$ |
| 4.5             | 3.2             | 0.71            |
| 3.9             | 3.9             | 1.0             |
| 3.5             | 4.3             | 1.23            |
| 3.2             | 4.5             | 1.41            |
| 2.9             | 4.9             | 1.69            |
| 2.6             | 5.2             | 2.0             |

| Table 2. Nozzle diameters of 6-hole lances for hot model. |
|-----------------|-----------------|-----------------|
| $D_{12°}$ (mm)  | $D_{24°}$ (mm)  | $D_{24°}/D_{12°}$ |
| 5.4             | 5.4             | 1.0             |
| 5.2             | 5.6             | 1.08            |
| 5.0             | 5.8             | 1.16            |
| 4.8             | 5.9             | 1.23            |
| 4.5             | 6.2             | 1.38            |
a minimum value at $D_{24\degree}/D_{12\degree} = 1.41$. The reason that $S_{\text{cold}}$ showed a minimum value will be discussed later.

The radial distributions of the jet pressure in the direction shown in Fig. 3(a) on the plane 200 mm distant from the 4-hole lances were plotted in Fig. 7. Pressure peaks for the 4-hole lances were located 25–40 mm off the center and the peak values were from 300 to 350 Pa. The radial distributions of the 6-hole lances in the direction shown in Fig. 3(b) were also plotted in Fig. 8. Peaks in the left and right sides corresponded to the jets from the nozzles with inclination angles of 12 and 24 degrees, respectively. The shifts of peaks from the center were 20–30 mm and 50–70 mm for nozzles of 12 and 24 degrees, respectively. The peak pressures of the jets from 12 degrees nozzles decreased and those of jets from 24 degrees nozzles increased with increase of the ratio of $D_{24\degree}/D_{12\degree}$.

3.2. Spitting and Jet Behavior in Hot Model Experiments

The spitting collection rates for the 6-hole lances in hot model experiments were plotted against the sampling height as shown in Fig. 9. The spitting collection rates decreased with an increase in the sampling height as in the cold model experiments. The spitting collection rates at a sampling height of 600 mm, $S_{\text{hot}}$ (kg/s), were plotted against the nozzle diameter ratio, $D_{24\degree}/D_{12\degree}$, as shown in Fig. 10. The spitting collection rate, $S_{\text{hot}}$, showed a minimum value at $D_{24\degree}/D_{12\degree} = 1.23$.

The radial distributions of jet pressure were plotted in Fig. 11 on the plane 400 mm distant from the 6-hole lances. The distributions were asymmetrical as in the cold model experiments. The peaks in the left and right sides correspond to the jet from the nozzle with inclinations of 12 and
24 degrees, respectively. As the ratio of nozzle diameters $D_{24} / D_{12}$ increased, the peak values in the left side decreased, whereas those in the right side increased.

4. Discussion

Normalized spitting rates, $S_{\text{cold}} / S_o$ and normalized spitting collection rate, $S_{\text{hot}} / S_o$ were plotted against $D_{24} / D_{12}$ to clarify effect of nozzle diameter ratio as shown in Fig. 12 where $S_o$ was the spitting value at $D_{24} / D_{12} = 1$. This figure indicates that a higher $D_{24} / D_{12}$ is needed in the cold model than in the hot model to obtain a minimum $S / S_o$. It is suggested that jets from straight nozzles used in the cold model were weaker than those from Laval nozzles in the hot model and are easier to coalesce with one another.

Peak pressure of jet is thought to have an influence on the spitting rate because spitting is induced by the jet blown to the bath surface. The peak pressures of jets from nozzles in the cold and hot model experiments were plotted against $D_{24} / D_{12}$ as shown in Figs. 13 and 14, respectively. In these figures, open marks indicate peak pressures of jets from 12 degrees nozzles, $P_{12}$ (Pa) and closed marks indicate those of jets from 24 degrees nozzles, $P_{24}$ (Pa). As $D_{24} / D_{12}$ increased, $P_{12}$ decreased and $P_{24}$ increased in both cold and hot model experiments. Maximum pressure of jets, $P_{\text{max}}$ (Pa), coincided with $P_{12}$ for lower $D_{24} / D_{12}$ and with $P_{24}$ for higher $D_{24} / D_{12}$.

Spitting values in the cold and hot model experiments, $S_{\text{cold}}$ and $S_{\text{hot}}$ were plotted against the maximum jet pressure, $P_{\text{max}}$, as shown in Figs. 15 and 16, respectively. These figures show that the spitting values increase with an increase in the maximum jet pressure and that the nozzle inclination angle has an effect on the spitting value. It is suggested that jets from nozzles with higher inclination angle result in more shift of peak from the center and that they lead to lower spitting rate.

The spitting phenomena in the present work could be summarized as follows: Droplets torn off by jets with less peak shift from 12 degree nozzles are likely to eject from the bath surface vertically and are easier to be collected as spitting particles, but droplets by jets with more peak shift from 24 degree nozzles are likely to eject diagonally and are more difficult to be collected. However, as diameters of 24 degree nozzles increase excessively, the amount of ejected droplets increases and it leads to higher spitting rate. Therefore, it is necessary to make an optimum pressure distribution of jet by designing nozzle arrangement in order to decrease spitting rate. 6-hole lances used in the present experiments are clearly convenient for the purpose because it can control pressure distribution by adjusting diameters and inclinations of nozzles simultaneously.
Regression analysis was applied to the experimental results in order to clarify the effects of maximum jet pressure $P_{\text{max}}$ and shift of pressure peak from the center. Spitting values were expressed with the empirical equations shown in Eqs. (1) and (2) for the cold and hot model.

\[
S_{\text{cold}} = 3.6 \times 10^{-17} P_{\text{max}}^{5.6} (D_{\text{peak}}/H)^{-0.55} \quad \text{(1)}
\]

\[
S_{\text{hot}} = 2.0 \times 10^{-16} P_{\text{max}}^{3.6} (D_{\text{peak}}/H)^{-1.15} \quad \text{(2)}
\]

where $D_{\text{peak}}$: shift of pressure peak from the center (m), $H$: height of lance tip from the bath surface (m).

**Figures 17 and 18** shows that spitting values, $S_{\text{cold}}$ and $S_{\text{hot}}$, are in good agreement with the empirical relationships obtained with regression analysis. The relationship in the cold model can be applied to not only the 6-hole lances but also the normal 4-hole lances as shown in Fig. 17.
The exponent of \( P_{\text{max}} \) to spitting value was higher in the cold model than in the hot model. In the hot model, the droplets were torn off from the liquid surface both by the kinetic energy of jet and by the “bubble burst”\( ^{10} \) induced by decarburization reaction just below the bath surface. The lower exponent of \( P_{\text{max}} \) to spitting value in the hot model suggests that existence of “bubble burst” lowered the influence of \( P_{\text{max}} \) relatively. And the absolute value of exponent of \( D_{\text{peak}}/H \) to spitting value was smaller in the cold model than in the hot model. The jet distributions in the cold model were observed to be broader than those in the hot model by comparing Figs. 8 and 11. It is thought to be due to the use of the straight type nozzles in cold model in spite of the use of the Laval type in the hot model. It is suggested that the width of jet distribution also affects the spitting behaviors. But further studies will be needed because there exists the difference of properties between in the cold model and in the hot model such as surface tension and density which affect the spitting behaviors.

5. Conclusions

By the cold and hot model experiments, the behavior of dynamic pressure of jets and spitting phenomena were investigated using 4- and 6-hole top blowing lances. Normal 4-hole lances had the same inclination angle of 10 or 15 degrees and newly designed 6-hole lances had two kinds of inclination angles of 12 and 24 degrees adjacently to control the dynamic pressure distribution of jets. The results obtained are as follows:

1. 4-hole lances showed higher spitting rates than 6-hole lances except for the ratio of nozzle diameters of \( D_{24}/D_{12} = 0.71 \) in the cold model experiments. Spitting rates in the 6-hole lances were influenced by \( D_{24}/D_{12} \) and there existed an optimum condition of \( D_{24}/D_{12} \) to minimize the spitting rates.

2. Observed dynamic pressure distribution of jets showed double peaks corresponding to jets from nozzles with inclination angles of 12 and 24 degrees.

3. With an increase in \( D_{24}/D_{12} \), peak pressure of jets from 24 degrees nozzles increased and that from 12 degrees nozzles decreased. It led to lower spitting rate because droplets generated by the jet from 24 degree nozzles were not likely to be collected as “spitting”. However, the spitting rate increased with an excessive increase in \( D_{24}/D_{12} \) because the amount of droplets ejected by the jets from 24 degree nozzles increased and could not be ignored.

4. Therefore, it is necessary to give an optimum pressure distribution of jet by designing nozzle diameters and inclination angles in order to decrease the spitting rate.

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