1. Introduction

Top and bottom combined blowing technology is widely used in BOF steelmaking process to improve bath agitation and mixing. The technology can promote metal–slag reactions, enhance decarbonization effect, lower oxidization of molten steel and slag at end point of blowing. It is important to choose correctly the number of bottom tuyeres and their arrangement for a special BOF to achieve the best bath stirring and the shortest bath mixing time. In this way, the merits of top and bottom combined blown converters can be revealed fully.

Numerical investigations on bottom tuyere configurations in metallurgical reactors have been carried out in order to enhance the bath stirring effect. Fiege et al. studied the influence of dispersed or collected arrangement of 4, 6 and 8 bottom nozzles on mixing behavior of converter bath. Their research results showed that grouping arrangement of 6 or 8 bottom tuyeres were most favorable for thorough bath mixing. The industrial application data indicated that the converter with asymmetric bottom tuyere arrangement showed better metallurgical results at tapping. Average tapping [O] decreased by 160 ppm and average tapping [C]×[O] reduced from 0.0031 to 0.0025. Average tapping (T.Fe)e content in slag decreased by 2.21 %, while average tapping (Mn)e increased by 0.029 %.

KEY WORDS: combined blown converter; bath mixing time; bottom tuyere configuration; physical modeling; industrial application.
plied in a BOF, it is not favorable to the bath mixing due to the formation of self-existent stirring sub-zones. Some researches\(^7\)–\(^9\) showed that application of asymmetric bottom tuyere configuration with suitable tuyere number for a given BOF can give shorter mixing times.

Six or four bottom tuyeres were used in the converters in Steelmaking Plant, Samming Iron and Steel Co., China. The bottom tuyeres were arranged symmetrically at the converter bottom (see case 1 and 4 in Fig. 2). In operation it was found that oxygen contents, products of carbon and oxygen contents in molten steel and FeO contents in slag at turn down were high, which meant that the converter bath stirring was inadequate. In order to decrease the oxidation of molten steel and slag and improve the reactions between metal and slag, water model experiments were carried out to optimize the bottom tuyere configuration for these converters. In the experiments, influence of symmetric and asymmetric bottom tuyere configurations with different tuyere number for the converters on their bath mixing was investigated by measuring the bath mixing time in the present work. The research result was applied to the converter No. 1 in the Steelmaking Plant and the effect of different bottom tuyere arrangements on the blowing index at converter tapping was compared.

2. Experimental

Schematic diagram of experimental apparatus in the physical modeling is shown in Fig. 1. A 1/8.5 reduced scale converter model was made of plexiglass. Water and air were used to simulate molten steel, oxygen and bottom injection gas, respectively. The air was supplied by a compressor which pumped the air into a gas container. The air flow rate was controlled by rotameters. Top lance was fabricated by a \(\Phi 22\) mm copper tube with a four-Laval-hole nozzle, made of plexiglass, too, at one end. The included angle between each nozzle center line and the lance center line was 12°. Bottom tuyeres were also made of \(\Phi 10\) mm and 20 mm long plexiglass rod with one end hollow. Three holes with a diameter of 1 mm were drilled at the other end of the rod. 20 mL of 0.2 g NaCl/mL solution was employed as a tracer for bath mixing time measurements. The tracer was added into the bath with a glass tube whose end was fixed and immersed into the position near to the bath surface and three conductivity probes were fixed on the model wall into the bath at three different positions. The probes were connected to three conductivity meters and the signals were recorded with a data acquisition system and a computer. In a mixing time experiment, when the steady state of bath flow was reached, the tracer solution was injected into the bath and time record started. The time when the bath conductivity reached 99% of the value corresponding to the steady state conditions was considered to be bath mixing time. Each experiment was repeated at least tow times to ensure the reproducibility of the measurements and the mean value of the measured data was treated as the bath mixing time.

The dynamic similarity between the model converter and the prototype was assured by maintaining the modified Froude number equivalence between the two vessels\(^10,\)\(^11\) shown as the following equation:

\[
\frac{u_m^2}{g L_m (\rho_m - \rho_g)} = \frac{u_p^2}{g L_p (\rho_p - \rho_g)} \quad \text{(1)}
\]

where, \(u\) is the velocity of gas injected into the bath, m/s, \(\rho\) density of the gas, kg/m\(^3\), \(L\) characteristic length, m, and \(g\) gravity acceleration, m/s\(^2\) and subscript \(m\) is for the model, \(p\) for the prototype, \(l\) for liquid phase and \(g\) for gas phase. The experimental conditions in the present work are shown

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**Table 1.** Experimental conditions used in the present work.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top gas flow rate (Q_{\text{top}}), Nm(^3)/h</td>
<td>33.5, 37.2, 41.0, 44.7</td>
</tr>
<tr>
<td>Bottom gas flow rate (Q_{\text{bot}}), Nm(^3)/h</td>
<td>0.47, 0.71, 0.94, 1.18, 1.42, 1.90, 2.38, 2.86</td>
</tr>
<tr>
<td>Oxygen lance height (h_{\text{top}}), mm</td>
<td>118, 141, 165, 188</td>
</tr>
<tr>
<td>Bath depth, mm</td>
<td>148</td>
</tr>
</tbody>
</table>

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in Table 1. Bottom tuyere configurations investigated in the experiments are shown in Figs. 2 and 3, respectively.

3. Experimental Results and Discussion

3.1. Symmetric Bottom Tuyere Configuration

Figure 4 shows the average bath mixing times as a function of top gas flow rates for the four kinds of symmetric bottom tuyere configurations in the top and bottom combined blown vessel. It can be observed from Fig. 4 that for these symmetric arrangements of bottom tuyeres the bath mixing times decrease with increase in top gas flow rates and high mixing times are observed, being 45–61 s. As top gas flow rate increases, momentum of the top gas left out of the top lance tip becomes larger, which results in increase of stirring energy and hence, decreases bath mixing times for the symmetrical bottom tuyere arrangements. The results in Fig. 4 show that the top gas from the top lance still has some effect on the bath mixing times in the symmetrical bottom tuyere case 1–4, which indicates that the stirring effect induced from bottom gas in case 1–4 is insufficient and unfavorable for overall bath mixing.

The influence of bottom gas flow rates on the average bath mixing times at different top lance height for bottom tuyere arrangement case 1 is presented in Fig. 5. It is known from Fig. 5 that the bath mixing times are almost the same with increase in bottom gas flow rates except the case with 118 mm of top lance height, which means that it is hardly possible to improve the bath stirring by increasing bottom gas flow rates for most top lance heights with such symmetric bottom tuyere arrangement.

Usually, when bottom gas flow rate increases, bath mixing time decreases due to stirring energy increase. But in bottom tuyere case 1 the mixing times hardly change among 141–188 mm top lance heights. This is due to some loss of stirring energy from the bottom gas because there are two bottom tuyeres arranged in the pitch circle with diameter ratio of 0.24\(D\), which causes interference between the top gas jet and the two bottom gas plumes. Such results were also presented by Oymo and Guthrie who pointed out that region between 0.2 and 0.35\(D\) in circular arrangement of tuyeres for combined blowing should be avoided. Another reason is that bottom tuyere case 1 is a symmetric arrangement and it divides the bath into 6 self-existent stirring sub-zones, which hardly forms horizontal flow and is unfavorable for the whole bath stirring and mixing. In the situation of 118 mm lance height, the cavity formed from top gas jet is narrow and deep, which results in less inter-

Fig. 2. Symmetric bottom tuyere configurations studied in this work.

Fig. 3. Asymmetric bottom tuyere configurations studied in this work.

Fig. 4. Bath mixing time in the combined converter with the bottom tuyere case 1–4.

Fig. 5. Bath mixing time in the combined converter with bottom tuyere case 1.
ference between these two gases and less stirring energy loss. Therefore, at 118 mm lance height the mixing times decrease with bottom gas flow rate at higher mixing time values.

### 3.2. Asymmetric Bottom Tuyere Configuration

The bath mixing times in combined blowing conditions were measured for the asymmetric bottom tuyere configurations (cases 5–8). The measurement results are shown in Fig. 6. It is obvious that the bath mixing times for the asymmetric bottom tuyere configurations are all shorter than those for the symmetric ones. The bath mixing times for these asymmetric arrangements are 36–47 s. As the top gas flow rates varies between 33.5–41.0 Nm$^3$/h, the bath mixing times of combined blowing do not change evidently, but when the top gas flow rate is higher than 41.0 Nm$^3$/h, the bath mixing time becomes long except arrangement case 5. During the experiments obvious bath oscillation was observed at top gas flow rate of 44.7 Nm$^3$/h. Such bath oscillation deteriorates the bath stirring and prolongs the bath mixing time since the bath oscillation has adverse influence on the flowing of bath fluid and mass transfer within the bath.

Of case 5–8, the tuyeres are arranged in a way of concentration and asymmetry. Among the case 6–8, 4 tuyeres are located at the completely same positions, while in case 5, there are 3 tuyeres among the 4 positions. It is the 4 tuyeres at the 4 positions along the trunnion direction in case 6 and 7 that help to produce horizontal flowing in the bath, which is favorable for overall bath mixing and results in lower bath mixing times than the case 1–4 where bottom tuyere are arranged symmetrically and dispersedly.

Figure 7 reveals the bath mixing times of combined blowing with bottom arrangement case 6 at different top lance heights as a function of bottom gas flow rates. As shown in this figure, the bath mixing times decrease with increase in bottom gas flow rates at all top lance heights due to the increase in bottom gas stirring energy. At lower bottom gas flow rate, the top lance height has a stronger effect on the bath mixing time. Lower top lance height benefits the bath mixing at low bottom gas flow rate. It is well known that lower top lance height will provide larger momentum to the bath when the top gas impinges on the bath surface. With increase in bottom blowing intensity, influence of top lance height on the bath stirring becomes less. This means that the bottom blowing has a dominative effect on the bath mixing in top and bottom combined blow converters, even though the bottom gas flow rate is much lower than the top gas flow rate.

Figure 8 indicates the bath mixing times with bottom configuration case 8 at 33.5 and 37.2 Nm$^3$/h of top gas flow rate and 141 and 165 mm of top lance height as a function of bottom gas flow rates. It can be found that the bath mixing times gradually decrease with the increase in bottom gas flow rates in this case for these operation conditions. The lowest bath mixing times are achieved at top gas flow rate of 37.2 Nm$^3$/h and lance height of 141 mm. With increase in top lance height to 165 mm, the bath mixing times become large. At lower top gas flow rate, 33.5 Nm$^3$/h, and higher lance height, 165 mm, the bath mixing times are the highest with low bottom gas flow rates less than about 1.0 Nm$^3$/h. As discussed as above, such variation of the bath mixing times with bottom and top gas flow rates and top lance height in case 8 is certainly related to the stirring energy provided by these factors. Higher bottom and top gas flow rates and lower top lance height would give stronger stirring energy and hence reduce the bath mixing times.

### 3.3. Bath Stirring with Only Bottom Blowing

Post-stirring operation with only bottom gas blowing is usually carried out at end point of blowing for further equilibrium between molten slag and liquid steel. Figures 9 and 10 present the bath mixing times with post-stirring for sym-
metric and asymmetric bottom tuyere configurations as a function of bottom gas flow rates, respectively. It is obvious in Fig. 9 that for bottom arrangement case 1 its post-stirring bath mixing times are the longest, being 77–79 s, and hardly change with increase in bottom gas flow rates. This means that such bottom tuyere arrangement is extremely unreasonable and the increase of bottom gas flow rates has hardly effect on the mixing of whole bath for such configuration. At lower bottom gas flow rates, case 2–4 show higher post-stirring bath mixing times. Only at higher bottom gas flow rates bottom case 2 and 3 have low post-stirring bath mixing times. Case 1 and 2 and case 3 and 4 have the same bottom tuyere number, 6 and 4 tuyeres, respectively, but their each other post-stirring bath mixing times are different largely for each situation, that is, case 2 and 3 have lower post-stirring bath mixing times than case 1 and 4, respectively. It is known from Fig. 2 that the bottom tuyeres in case 2 and 3 are arranged more concentratedly compared to those in case 4. Concentrative bottom tuyere arrangements can reduce barriers to mixing and hence, decrease the bath mixing times. Similar results were also obtained by Fiege et al.\textsuperscript{11} and by Paul and Ghosh.\textsuperscript{12} As discussed before, case 1 divided the bath into 6 self-existent stirring sub-zones which resulted in higher post-stirring bath mixing times. For the asymmetric bottom tuyere configurations studied in the present work their post-stirring bath mixing times are shorter, being 28–43 s, than the symmetric bottom arrangements. Comparing Fig. 3 to Fig. 2, it is obvious that the bottom tuyeres in case 5–8 are more concentrated than those in case 1–4. Additionally the bottom tuyere arrangement case 5–8 are asymmetric. As having been already explained, such concentrated and asymmetric bottom tuyere arrangements are favorable for overall bath mixing and hence give lower mixing times due to reduction of mixing barriers and tendency of horizontal flowing.

The above experimental results reveal that the bath stirring with asymmetric bottom tuyere configurations is better than that with symmetric ones. For the symmetric arrangements stirring cells formed in the bath are easy to form self-governed ones each other, which causes in low mass transfer rate in the whole bath. For the asymmetric arrangements horizontal flowing tendency can be enhanced in the bath besides the vertical flowing, which is favorable to the mixing between the stirring cells and speeds up the mass transfer rate in the whole bath. Therefore, the asymmetric bottom tuyere configurations have shorter bath mixing times.

4. Plant Results

Bottom tuyere arrangement case 1 was the former configuration of a top and bottom combined blown converter in the steelmaking plant, Sanming Iron and Steel Co., China. When a new campaign started, bottom tuyere arrangement case 8 was chosen to implement at the bottom of the converter due to its six bottom tuyere arrangement although the bottom arrangement case 6 and 7 have a bit lower bath mixing times, because the plant was worried about clogging of some of bottom tuyeres in operation. The metallurgical data at tapping were compared for the two kinds of bottom arrangements at almost the same average tapping $\left[ C \right]_e$ content and tapping temperature $T_e$. The average results for these two bottom configurations are shown in Table 2. As shown in the table, the average tapping data with case 8 bottom arrangement are better than those with case 1. Average tapping $\left[ O\right]_e$ content is lowered by 160 ppm at almost the same average tapping $\left[ C\right]_e$ content, average tapping $\left[ C\right]_e \times \left[ O\right]_e$ is nearer to the thermodynamic value, and average tapping $\left[ P\right]_e$ is lower even though average tapping $\left( T.Fe\right)_e$ content in molten slag is reduced by 2.21% for bottom configuration case 8 due to its better bath mixing, while average tapping $\left[ Mn\right]_e$ is higher.

5. Conclusions

Influence of symmetric and asymmetric bottom tuyere configurations on bath mixing behavior in a top and bottom combined blown converter has been investigated in the present work. The following conclusions can be drawn out from the investigation.

(1) Asymmetric and concentrated bottom arrangement has shorter bath mixing time than symmetric bottom arrangement studied in this work, not only in the case of
only bottom blowing but also in the case of top and bottom blowing.

(2) Bath oscillation in converters with too high top gas flow rates would deteriorate the bath stirring and prolong the bath mixing time in the case of asymmetric bottom tuyere configurations.

(3) Bath stirring of top and bottom combined blown converters can be improved by bottom tuyere configuration optimization with asymmetric and concentrated bottom system.

(4) Metallurgical data at tapping with bottom arrangement case 8 were improved evidently, compared to the former bottom arrangement case 1. Average tapping [O]e content was decreased by 160 ppm, average tapping [C]e×[O]e lowered from 0.0031 to 0.0025, average tapping [Mn]e content increased by 0.029% and average tapping (TFe) e content in slag reduced by 2.21%.

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